

*(The Path to)*  
*Undulant Cosmologies*

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*Fermilab*

Delaware Particle / Astrophysics Seminar · 9 March 2006

## I Neutrino Observatories: Expectations

Cosmic  $\nu$  flux may exceed atmospheric background at  $E_\nu \approx$  few TeV

*prospect for sources · characterize sources · study  $\nu$  properties*

Sources include AGN (at  $\sim 10^2$  Mpc)  $1 \text{ Mpc} \approx 3.1 \times 10^{22} \text{ m}$

$pp$  or  $p\gamma \Rightarrow \approx$  numbers of  $\pi^+ \pi^0 \pi^-$

$\pi^+ + \pi^0 + \pi^- \Rightarrow 2\gamma + 2\nu_\mu + 2\bar{\nu}_\mu + 1\nu_e + 1\bar{\nu}_e$

$$\Phi_{\text{std}}^0 = \{\varphi_e^0 = \frac{1}{3}, \varphi_\mu^0 = \frac{2}{3}, \varphi_\tau^0 = 0\} \quad (\nu = \bar{\nu})$$

Detection (in volumes  $\rightarrow 1 \text{ km}^3$ )

$(\nu_\mu, \bar{\nu}_\mu)N \rightarrow (\mu^-, \mu^+) + \text{anything}$

Can we achieve efficient, calibrated  $(\nu_e, \bar{\nu}_e)$  detection?

Good  $(\nu_\tau, \bar{\nu}_\tau)$  detection, NC capability desirable

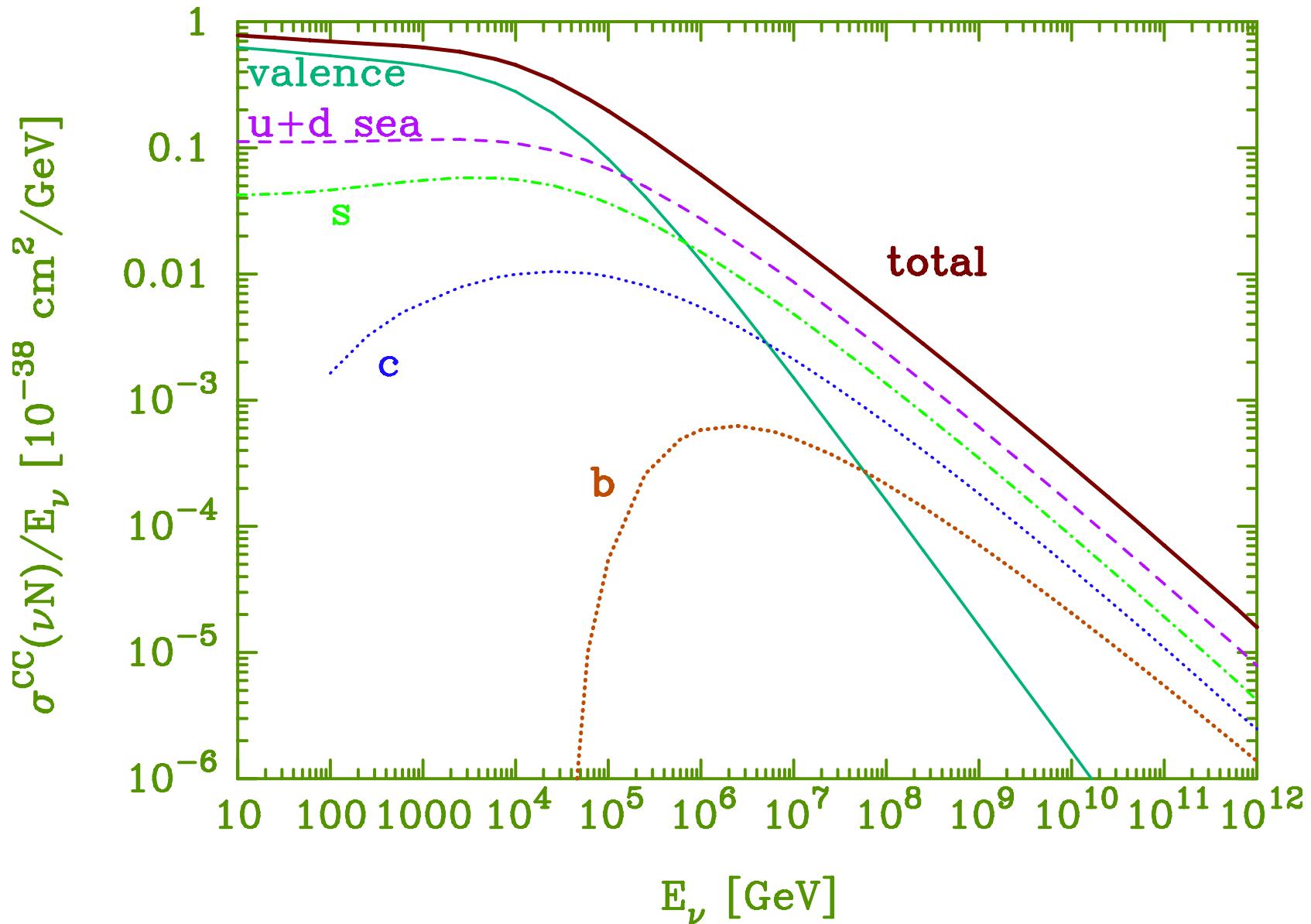
$\nu_\mu N \rightarrow \mu^- + \text{anything}$

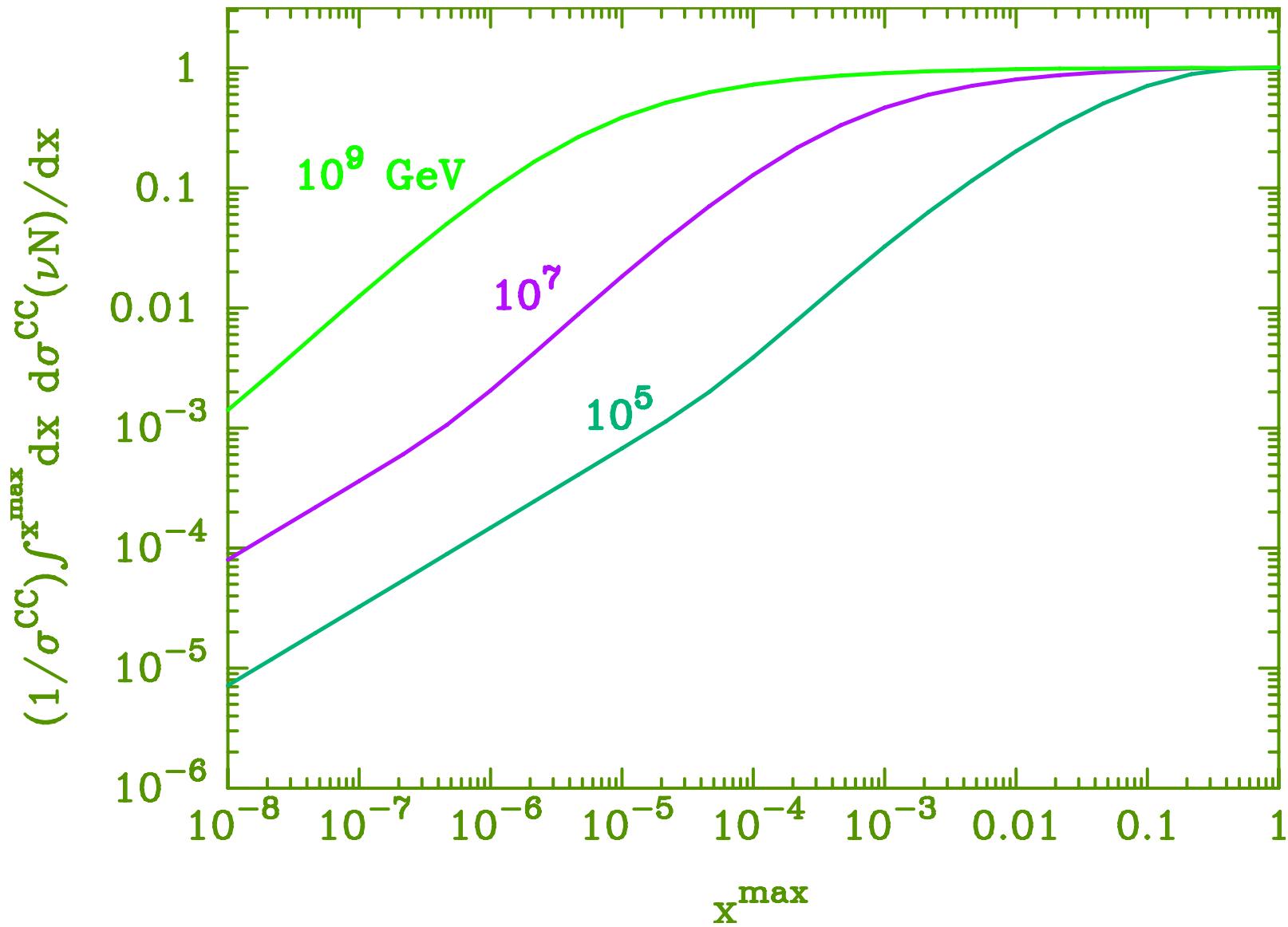
$$\frac{d^2\sigma}{dxdy} = \frac{2G_F^2 M E_\nu}{\pi} \left( \frac{M_W^2}{Q^2 + M_W^2} \right)^2 [xq(x, Q^2) + x\bar{q}(x, Q^2)(1 - y)^2]$$

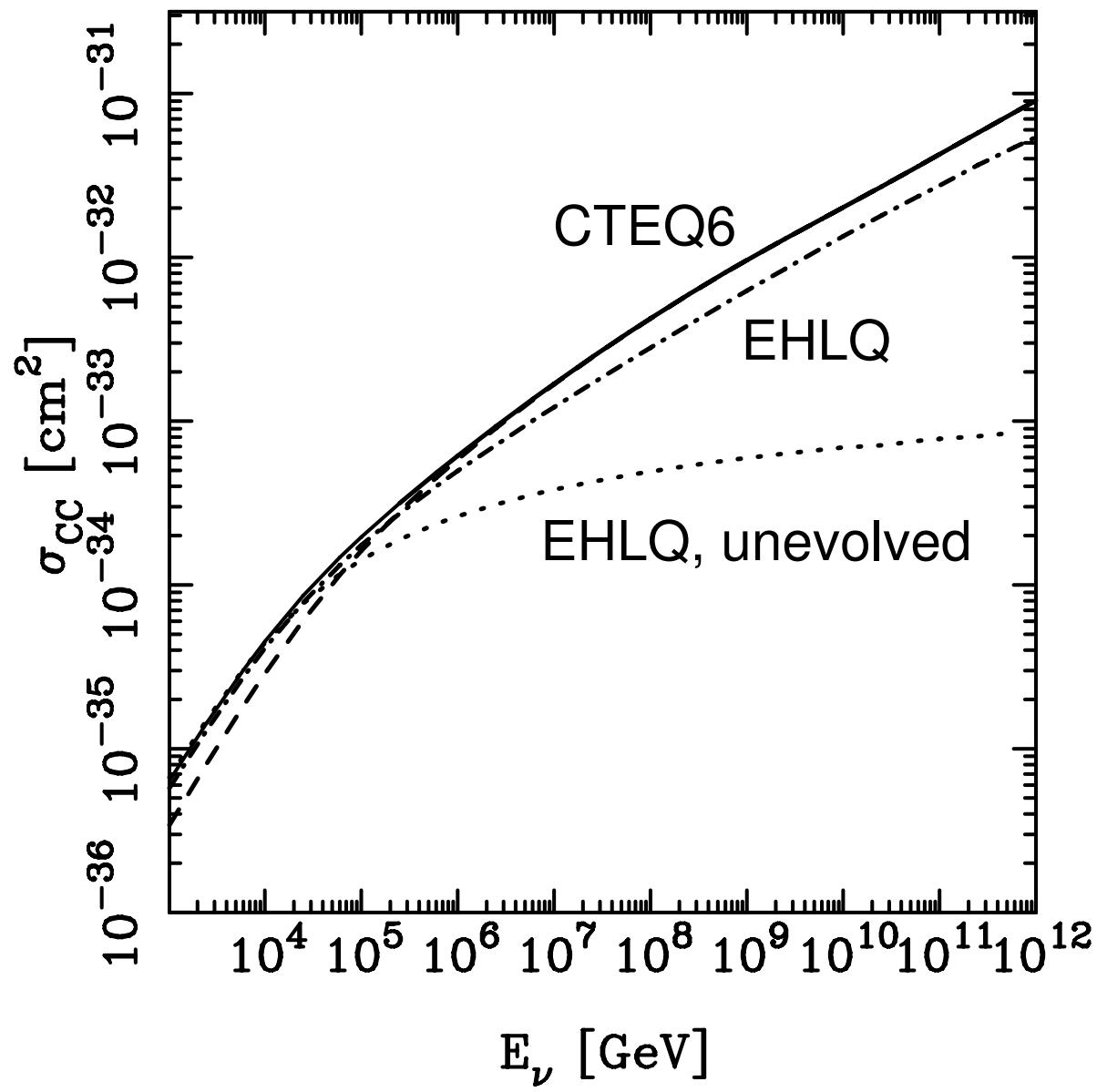
$$q(x, Q^2) = \frac{u_v(x, Q^2) + d_v(x, Q^2)}{2} + \frac{u_s(x, Q^2) + d_s(x, Q^2)}{2} \\ + s_s(x, Q^2) + b_s(x, Q^2)$$

$$\bar{q}(x, Q^2) = \frac{u_s(x, Q^2) + d_s(x, Q^2)}{2} + c_s(x, Q^2) + t_s(x, Q^2),$$

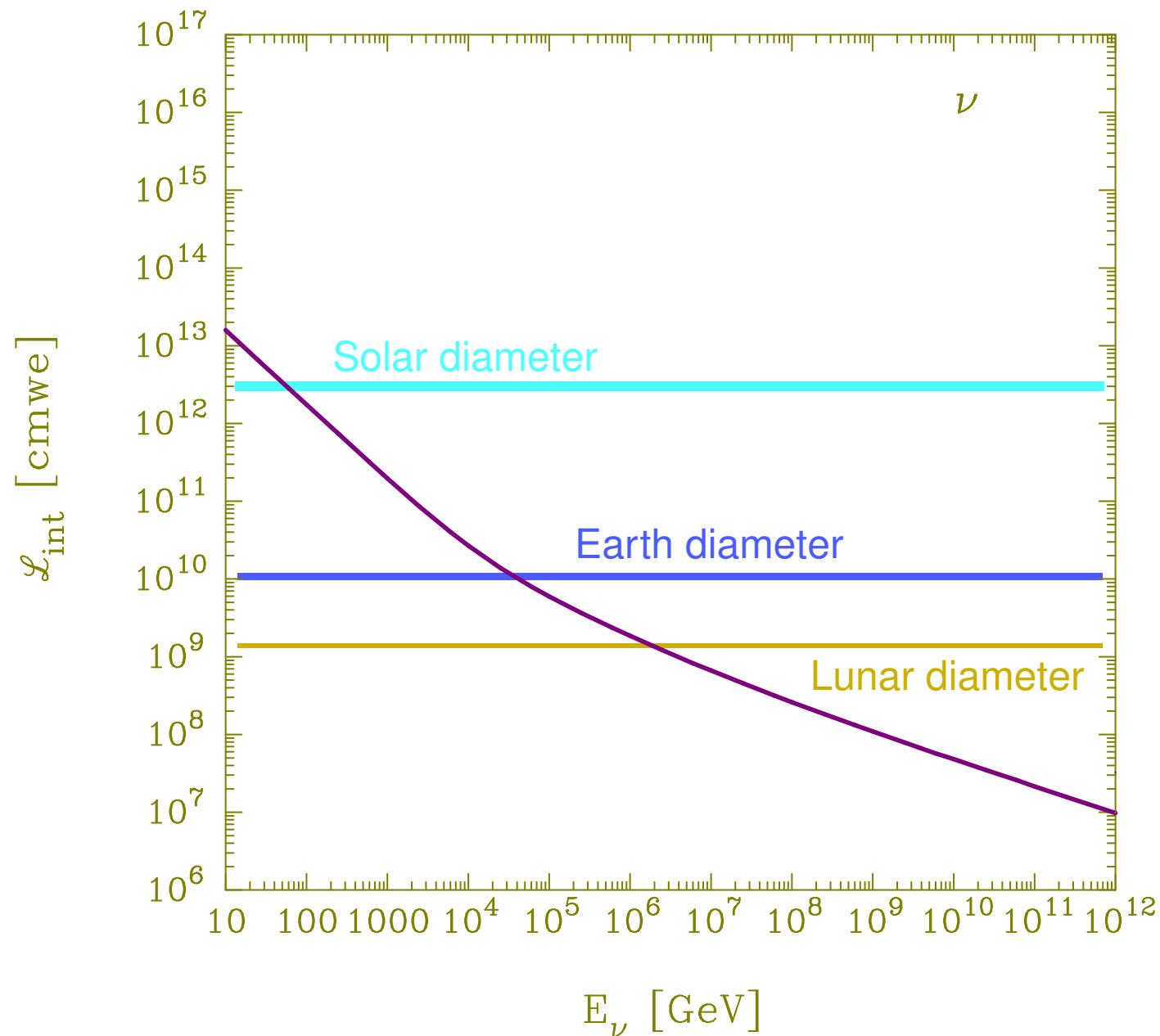
. . . isoscalar nucleon

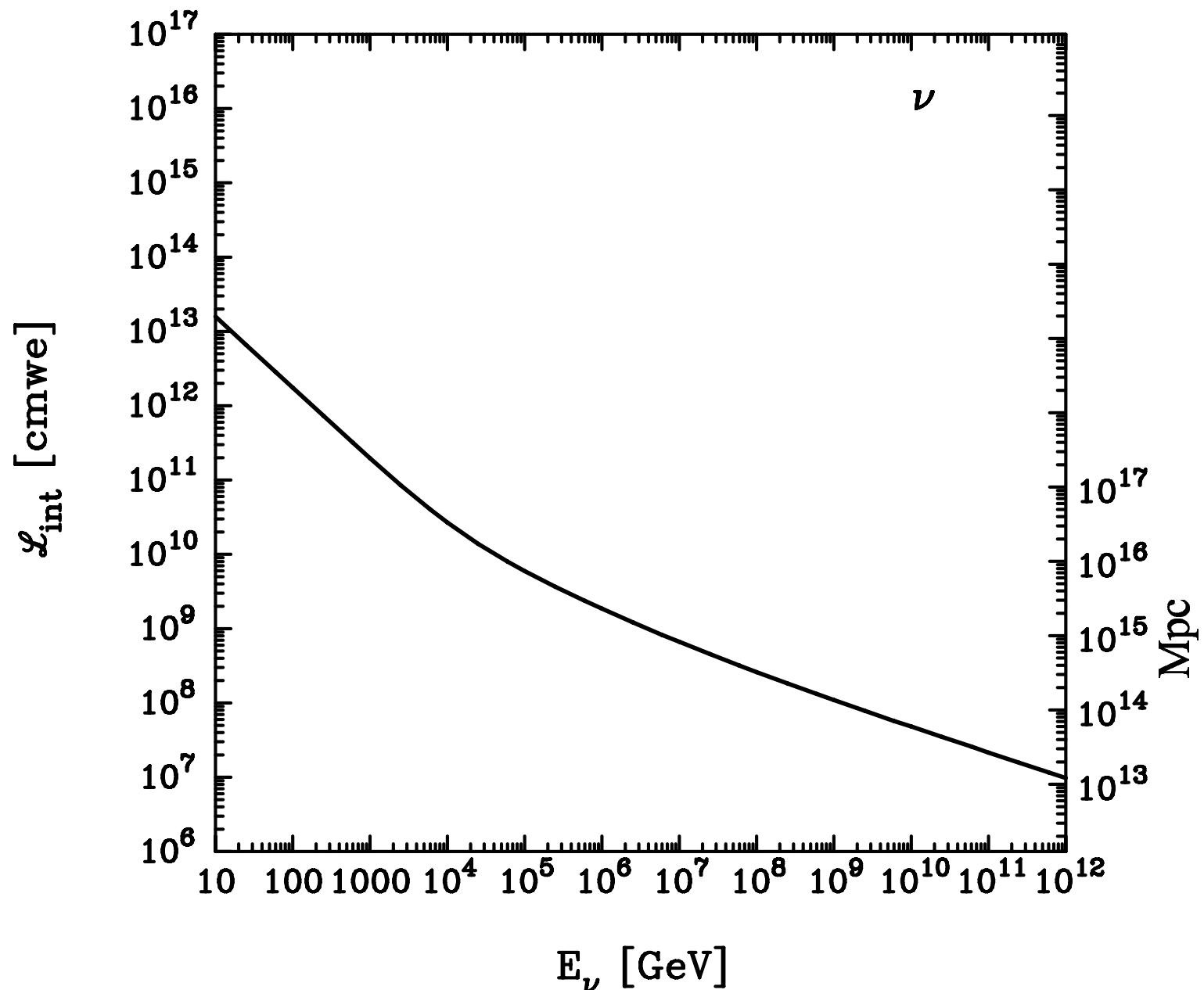


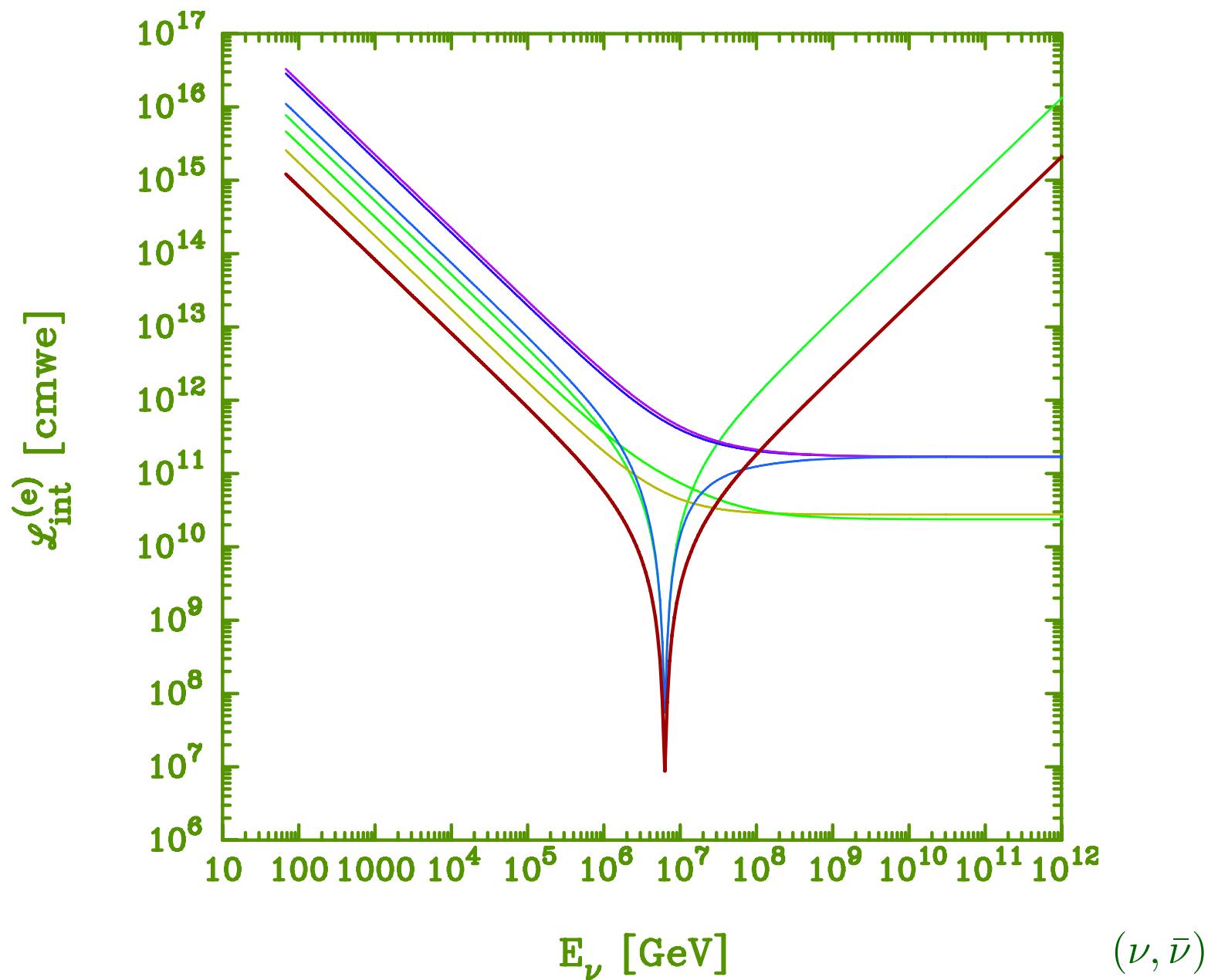




M. H. Reno



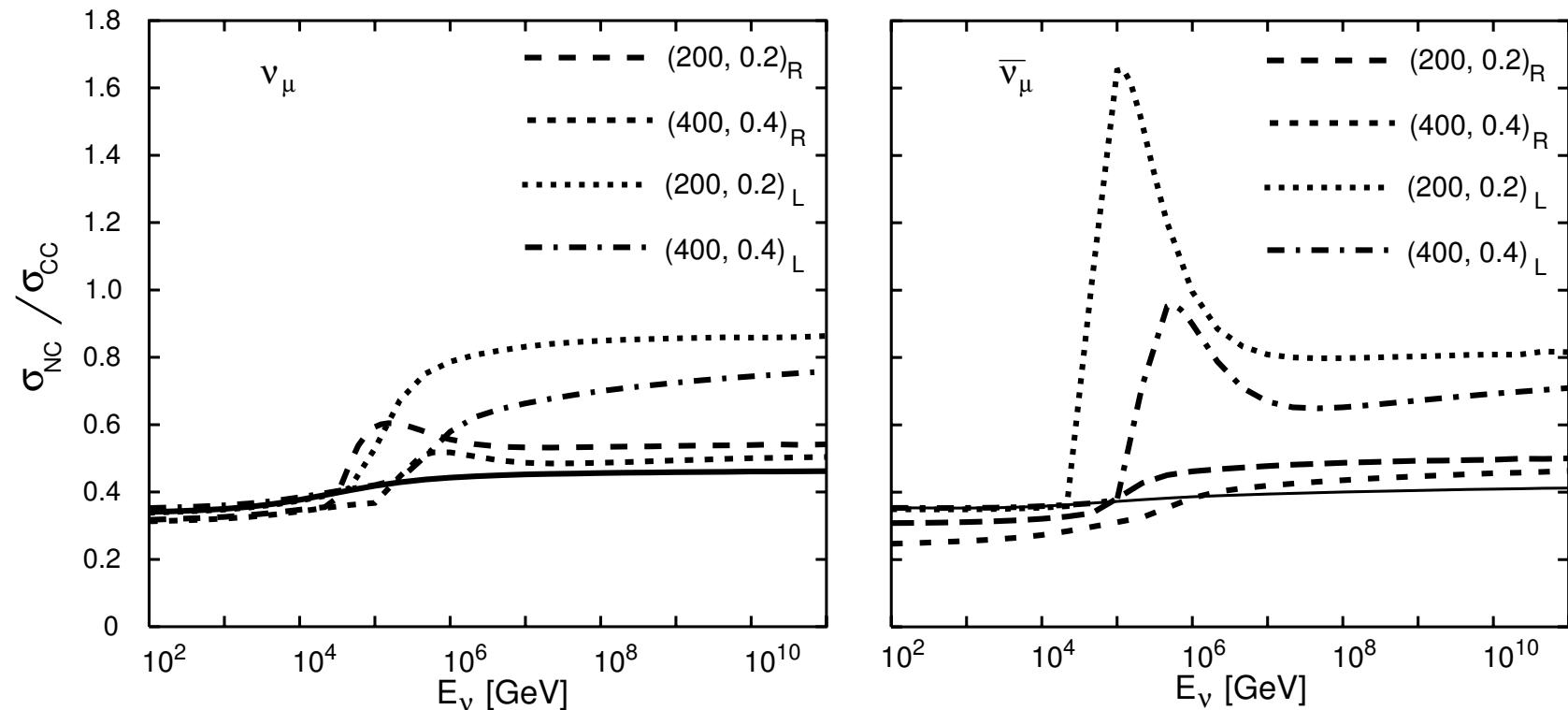




## II New Physics in $\nu N$ interactions?

*NC/CC an important diagnostic*

$\tilde{d}_{L,R}^k$  production through  $\cancel{R}$  interactions:



$(\tilde{m}, \lambda')$

### III Influence of Neutrino Oscillations

Flux at Earth  $\Phi = \{\varphi_e, \varphi_\mu, \varphi_\tau\} \neq \Phi^0 = \{\varphi_e^0, \varphi_\mu^0, \varphi_\tau^0\}$  source fluxes

Vacuum oscillation length is short; for  $|\Delta m^2| = 10^{-5}$  eV $^2$ ,

$$L_{\text{osc}} = 4\pi E_\nu / |\Delta m^2| \approx 2.5 \times 10^{-24} \text{ Mpc} \cdot (E_\nu / 1 \text{ eV})$$

... a fraction of Mpc even for  $E_\nu = 10^{20}$  eV

*$\nu$  oscillate many times between cosmic source and terrestrial detector*

Also, over long paths, cosmic neutrinos are vulnerable to decay processes that would not affect terrestrial or solar experiments.

## ... Neutrino Oscillations

$$(\text{flavor}) \nu_\alpha = \sum_i U_{\beta i} \nu_i \ (\text{mass})$$

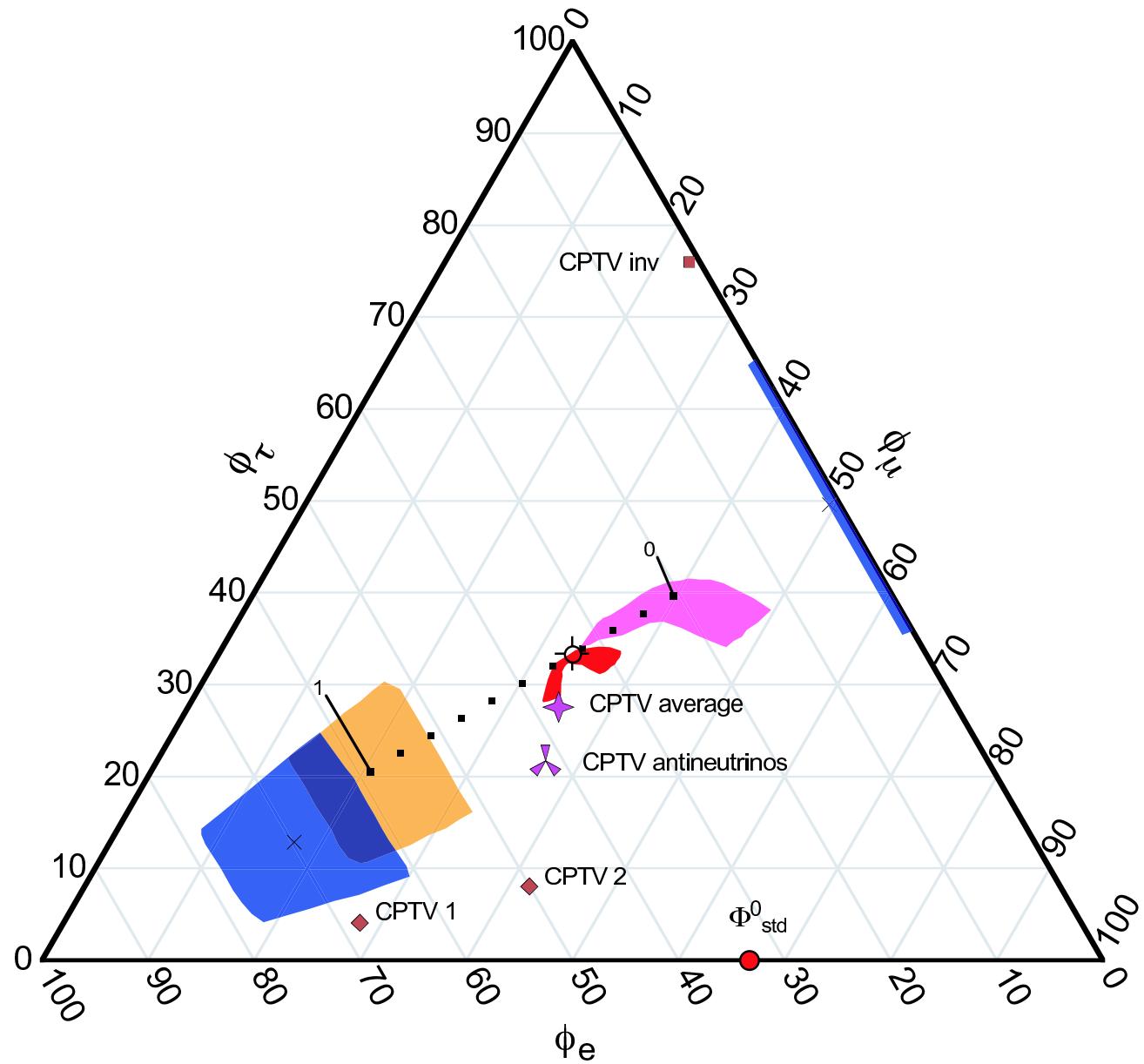
Idealize  $\sin \theta_{13} = 0$ ,  $\sin 2\theta_{23} = 1$ , write  $x = \sin^2 \theta_{12} \cos^2 \theta_{12}$ .

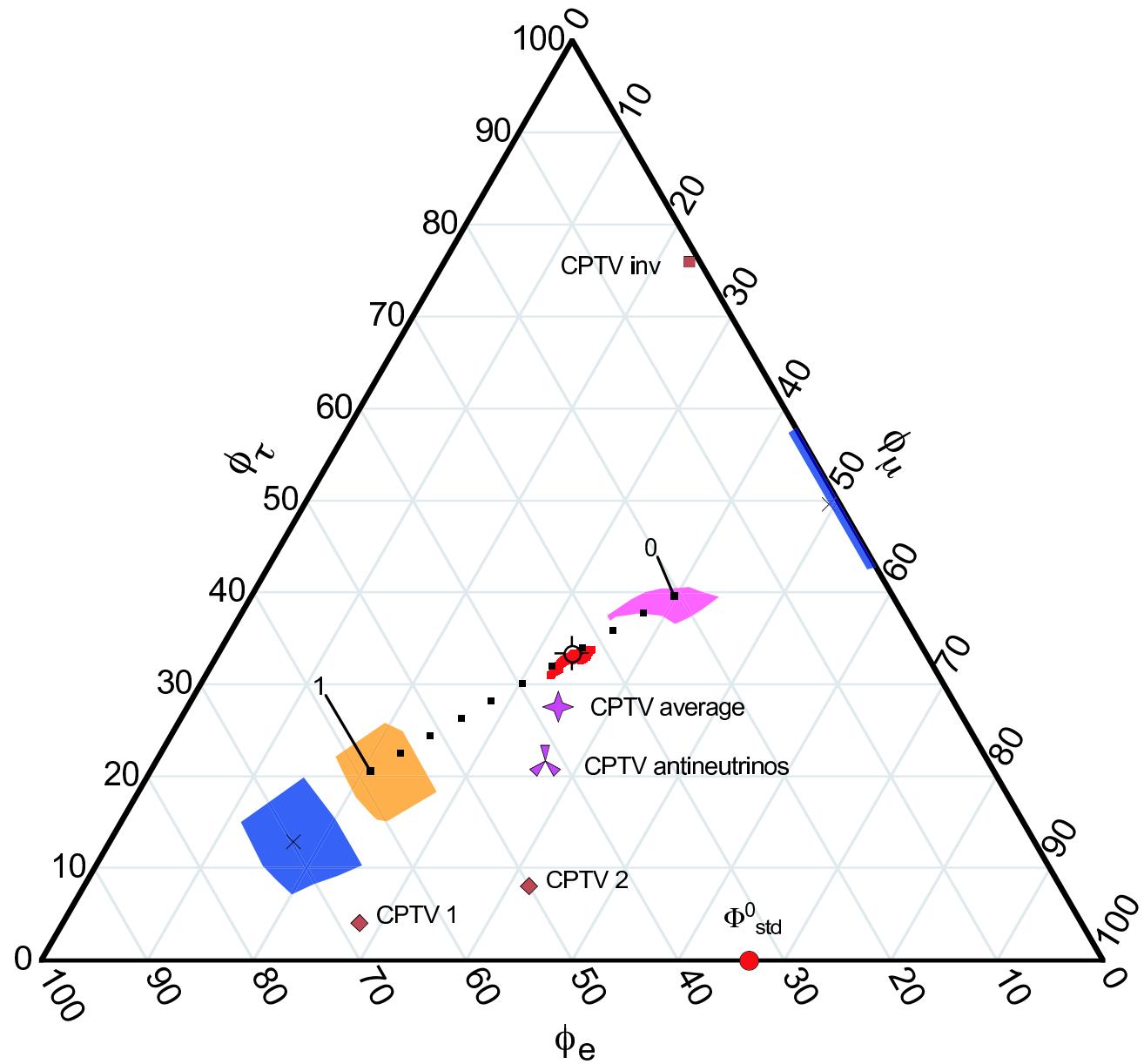
$$U_{\text{ideal}} = \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12}/\sqrt{2} & c_{12}/\sqrt{2} & 1/\sqrt{2} \\ s_{12}/\sqrt{2} & -c_{12}/\sqrt{2} & 1/\sqrt{2} \end{pmatrix}$$

Transfer matrix  $\mathcal{X}$ :  $\Phi^0$  (source)  $\rightarrow$   $\Phi$  (detector); Over many oscillations,

$$\mathcal{X}_{\text{ideal}} = \begin{pmatrix} 1 - 2x & x & x \\ x & \frac{1}{2}(1-x) & \frac{1}{2}(1-x) \\ x & \frac{1}{2}(1-x) & \frac{1}{2}(1-x) \end{pmatrix} \quad \text{Parke}$$

$$\boxed{\mathcal{X}_{\text{ideal}} : \Phi_{\text{std}}^0 \rightarrow \{\varphi_e = \frac{1}{3}, \varphi_\mu = \frac{1}{3}, \varphi_\tau = \frac{1}{3}\}}$$

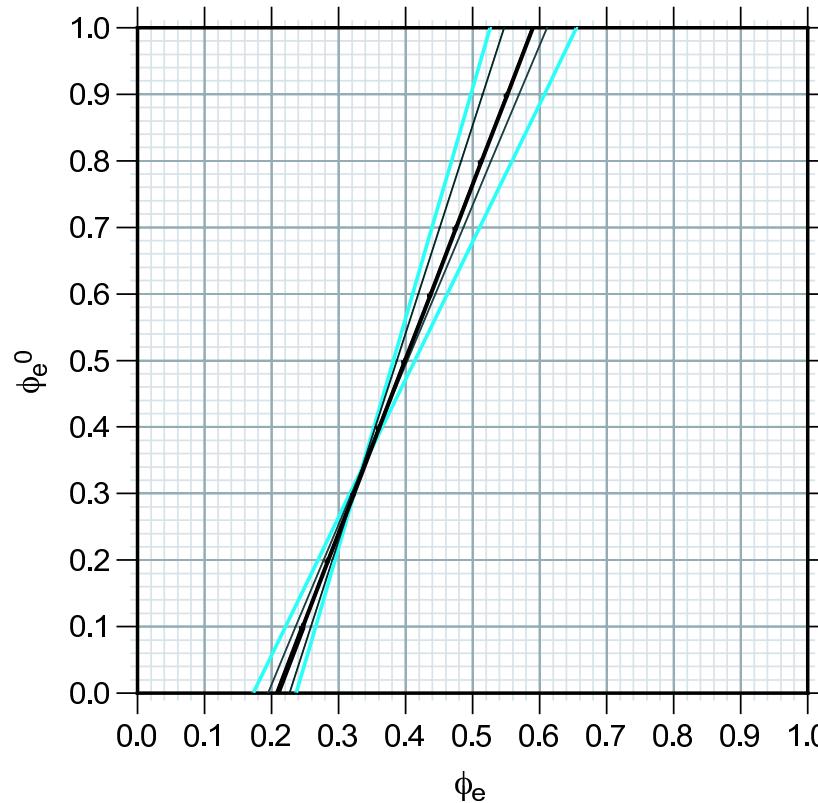




## IV Reconstructing the $\nu$ Mixture at the Source

$\nu_\mu, \nu_\tau$  fully mixed  $\Rightarrow$  can't fully characterize  $\Phi^0$

Reconstruct  $\nu_e$  fraction at source using  $\mathcal{X}_{\text{ideal}}$ :  $\varphi_e^0 = (\varphi_e - x)/(1 - 3x)$



Extreme  $\varphi_e$  implicates unconventional physics

## V

## Influence of Neutrino Decays

Nonradiative decays  $\nu_i \rightarrow (\nu_j, \bar{\nu}_j) + X$  not very constrained:

$$\tau/m \gtrsim 10^{-4} \text{ s/eV}$$

If only lightest neutrino survives, flavor mix at Earth is independent of composition at source

Normal hierarchy

$$m_1 < m_2 < m_3:$$

$$\varphi_\alpha = |U_{\alpha 1}|^2$$

$$\Phi_{\text{normal}} \approx \{0.70, 0.17, 0.13\}$$

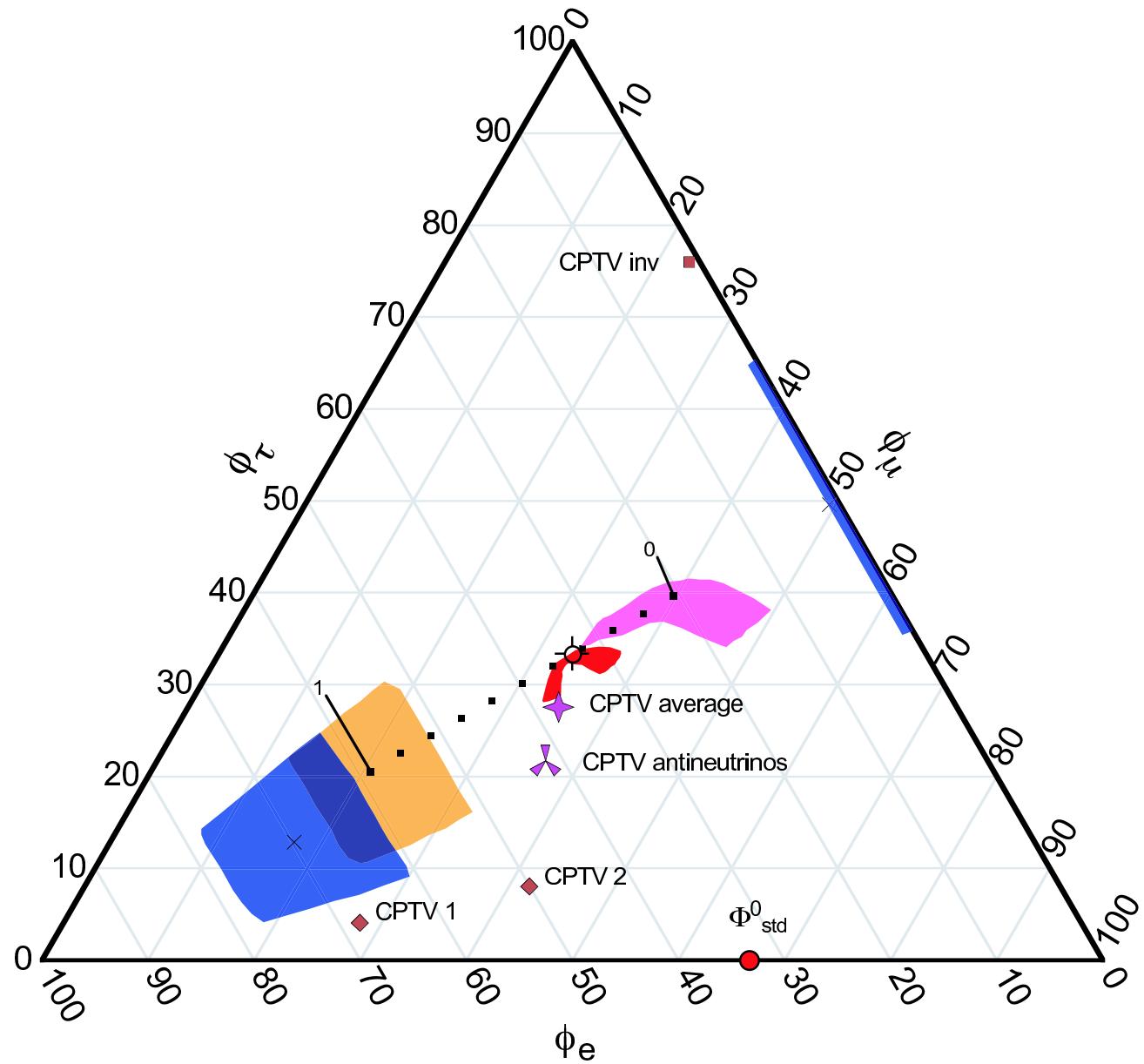
Inverted hierarchy

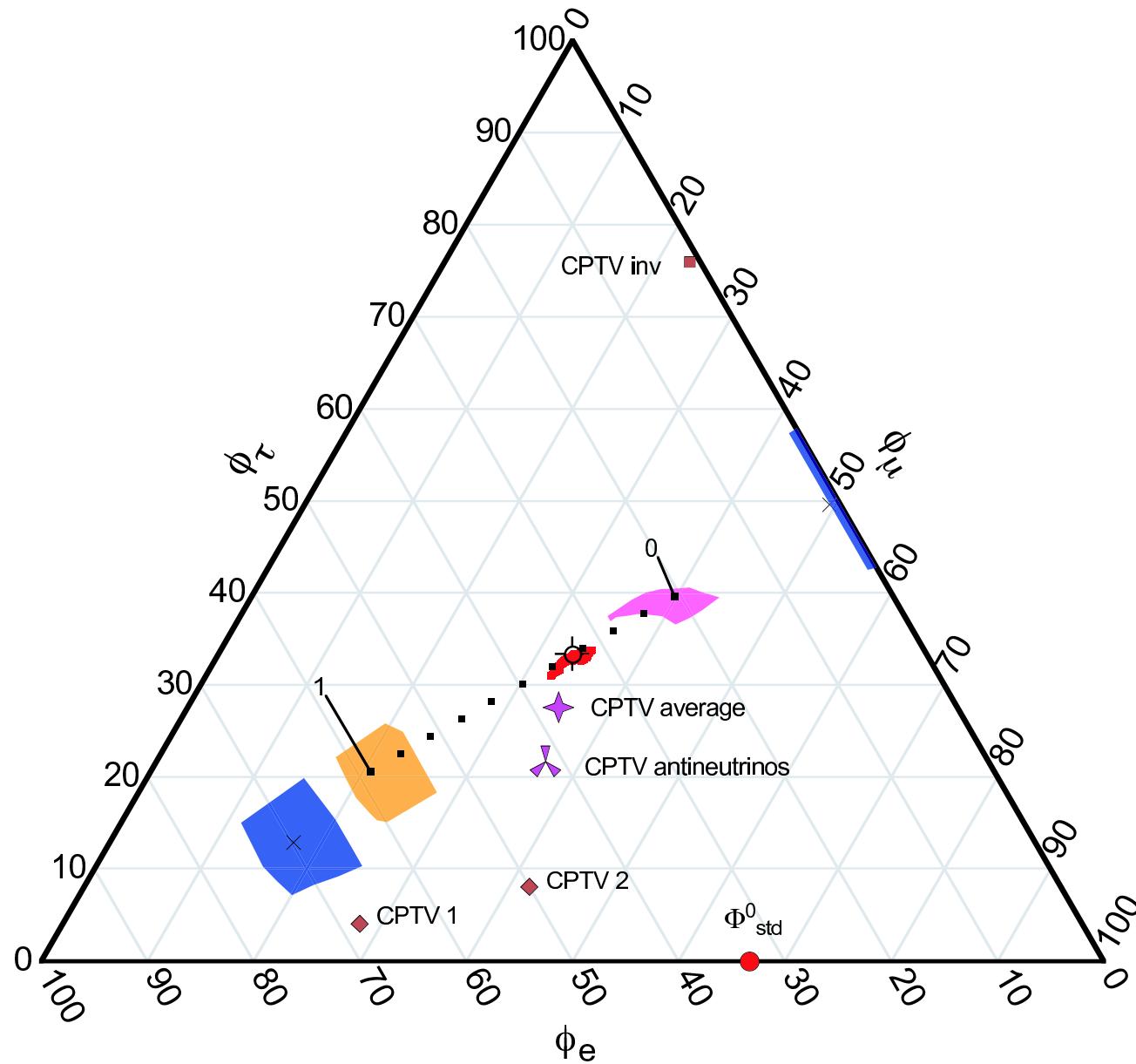
$$m_1 > m_2 > m_3:$$

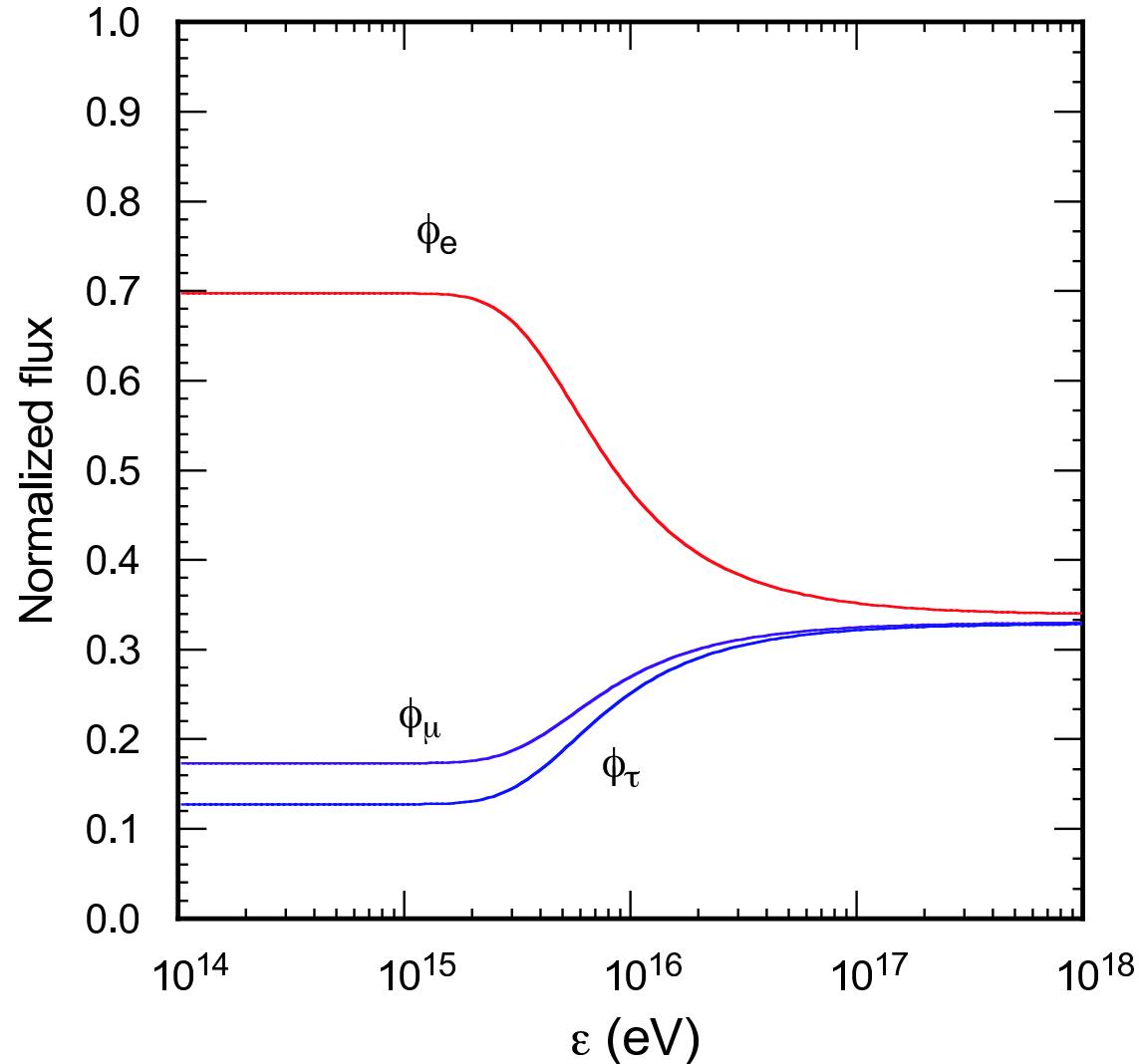
$$\varphi_\alpha = |U_{\alpha 3}|^2$$

$$\Phi_{\text{inverted}} \approx \{0, 0.5, 0.5\}$$

far from  $\Phi_{\text{std}} = \{\frac{1}{3}, \frac{1}{3}, \frac{1}{3}\}$

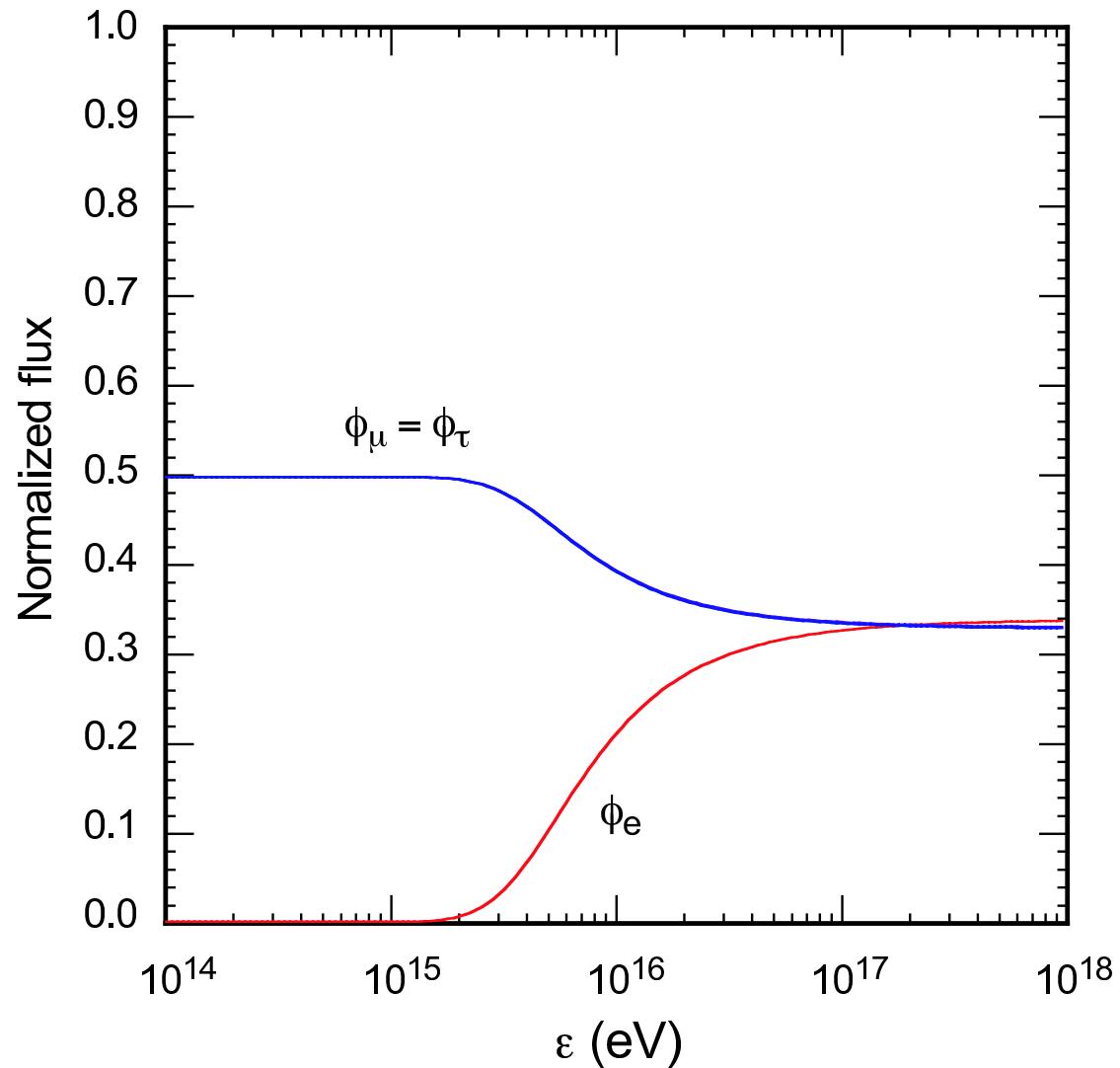






$$E_\nu = \varepsilon(1 \text{ s/eV}) / (\tau_\nu / m_\nu) \cdot L / (100 \text{ Mpc})$$

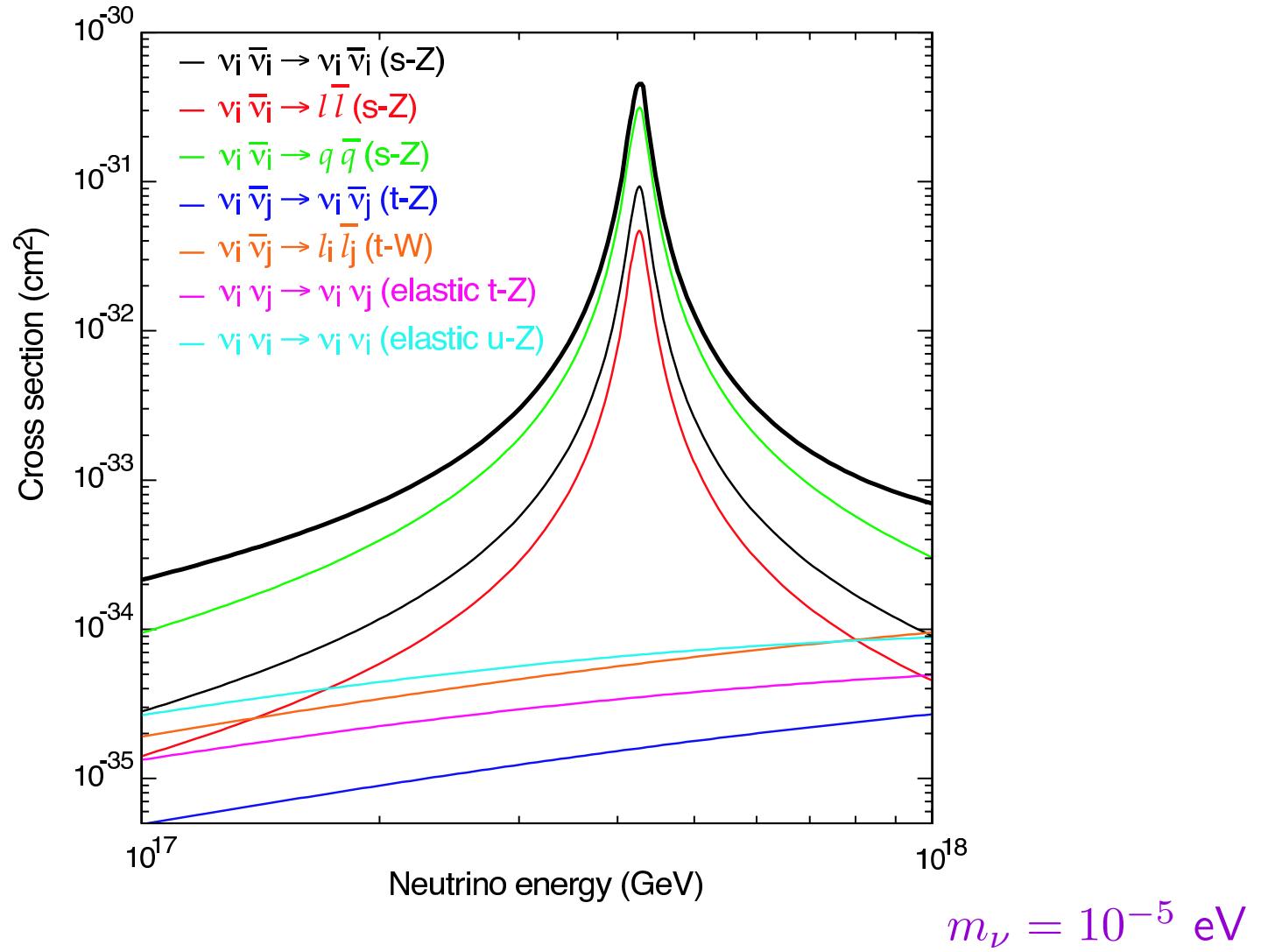
Normal hierarchy



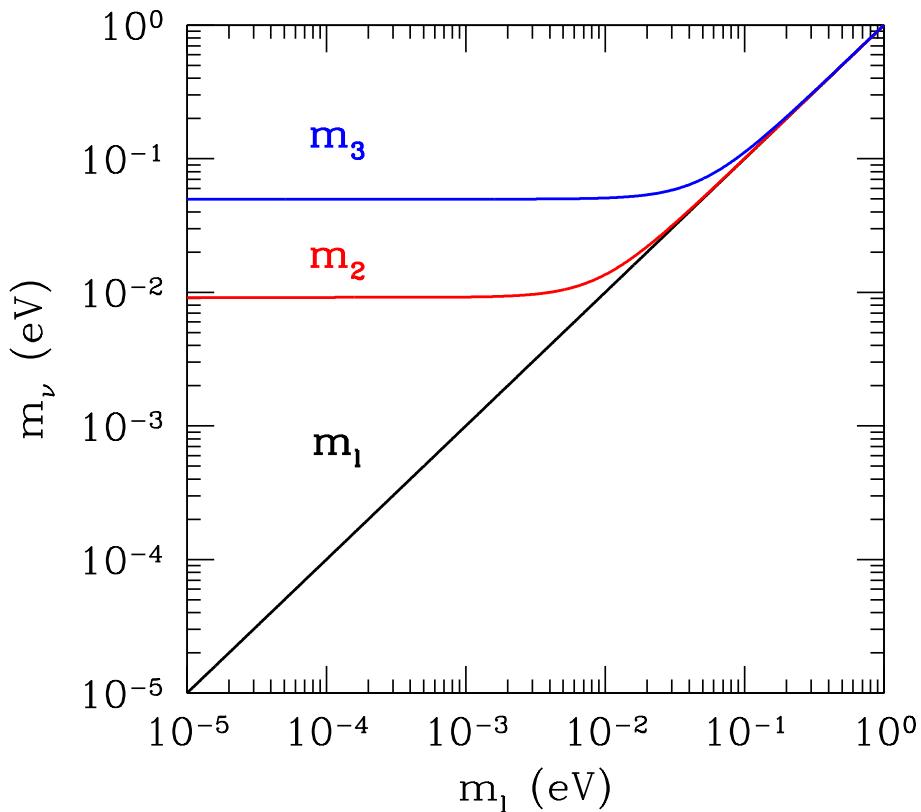
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Inverted hierarchy

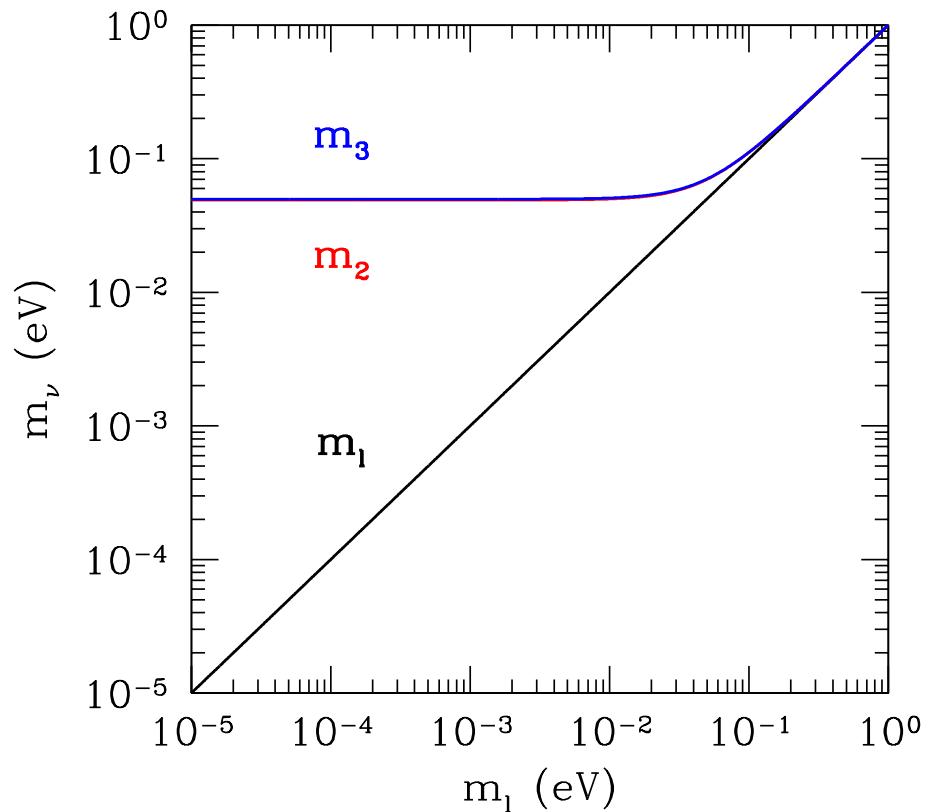
## VI UHE $\nu$ annihilation on $\nu$ relics



## Normal hierarchy



## Inverted hierarchy

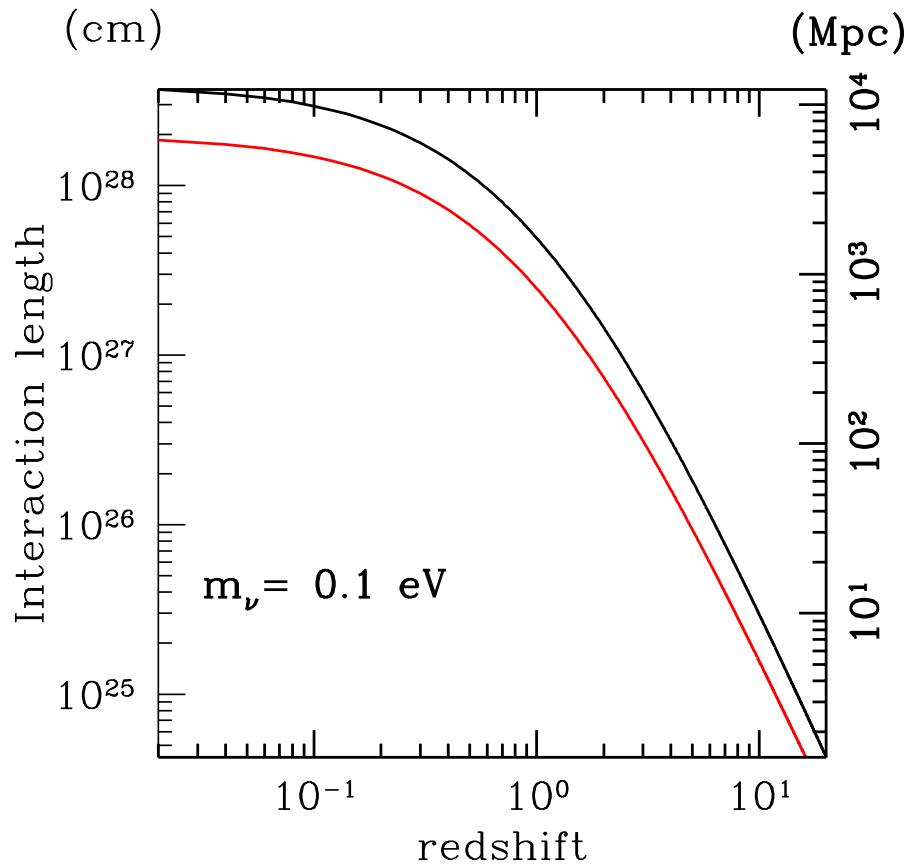
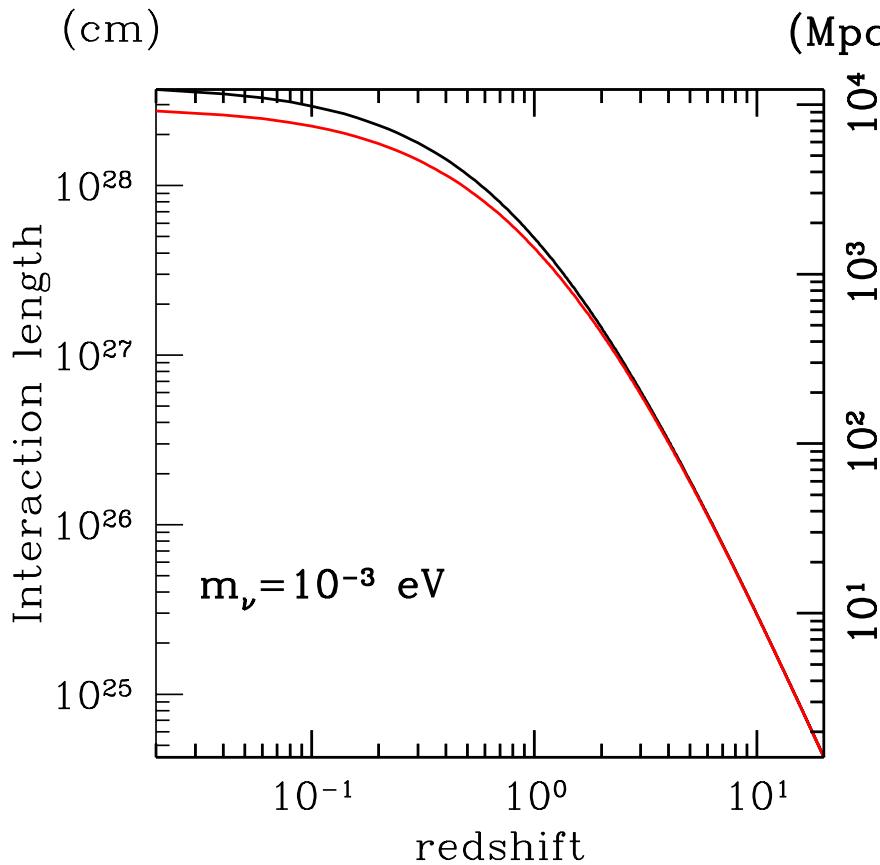


Animation

## Interaction lengths on $Z^0$ resonance:

Dirac

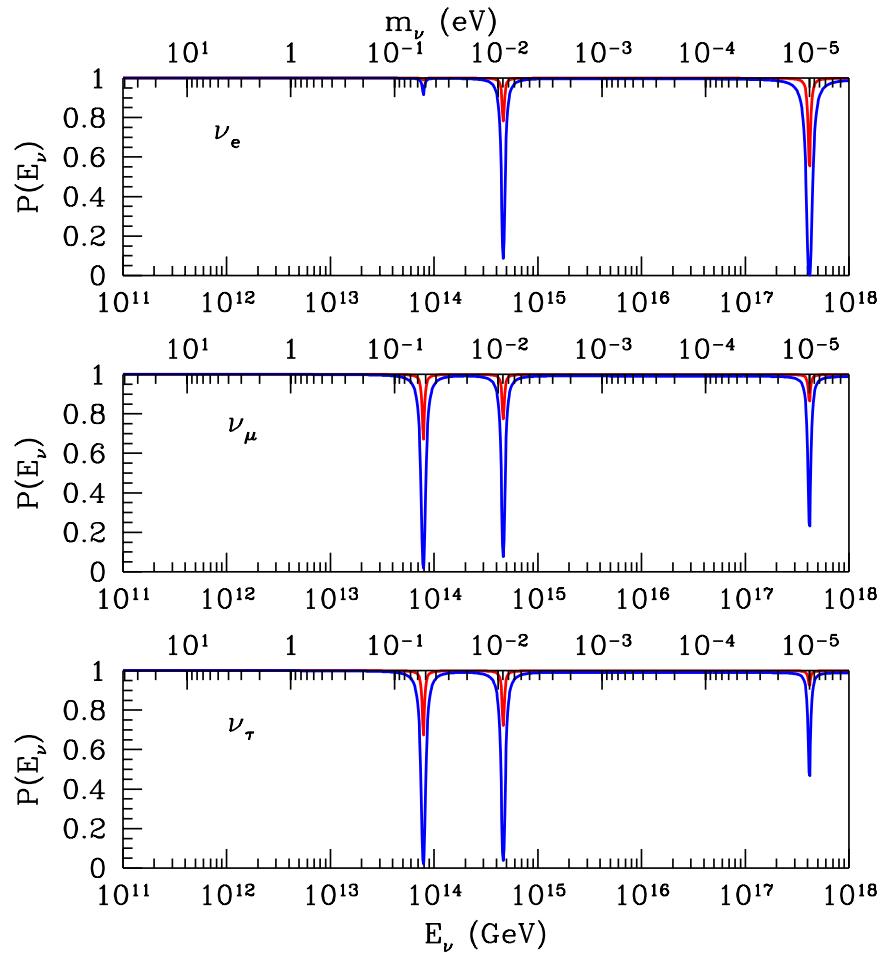
Majorana



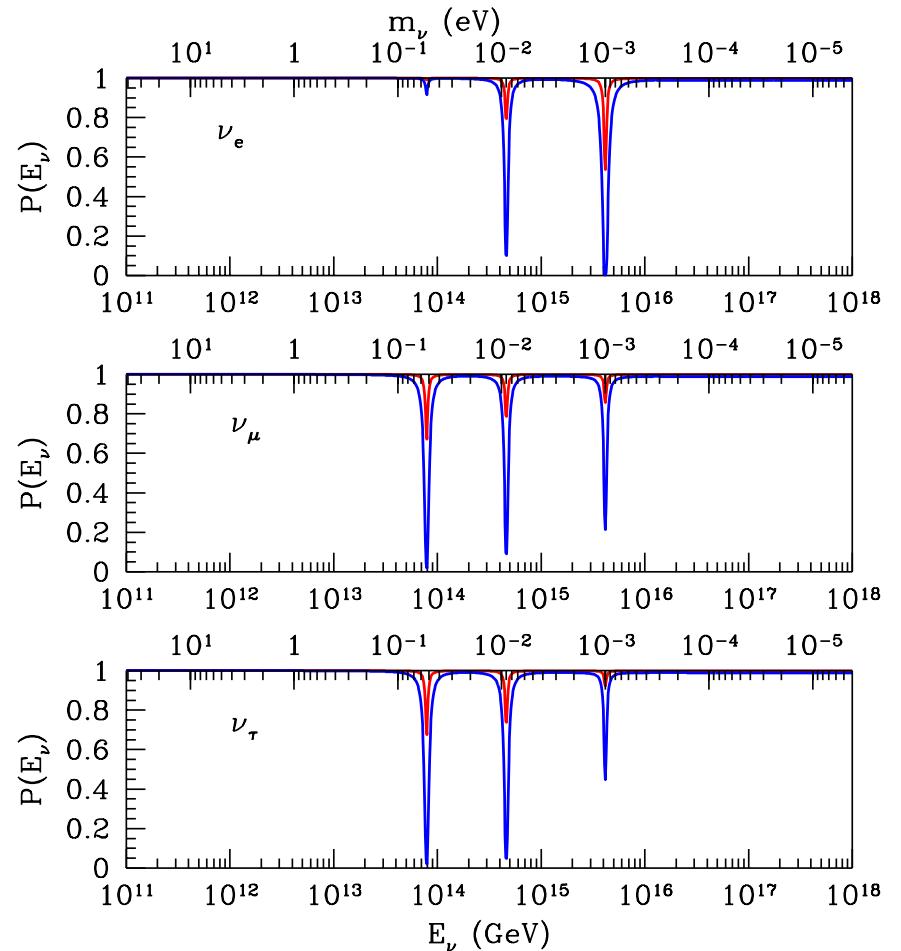
$\nu$  number density now:  $56 \text{ cm}^{-3}, \propto (1+z)^3$

$1.4 \text{ Mpc} = 39 \text{ Gly}$

Fable: *I-o-o-o-o-n-g* path ( $10^4$  or  $10^5$  Mpc) in current Universe

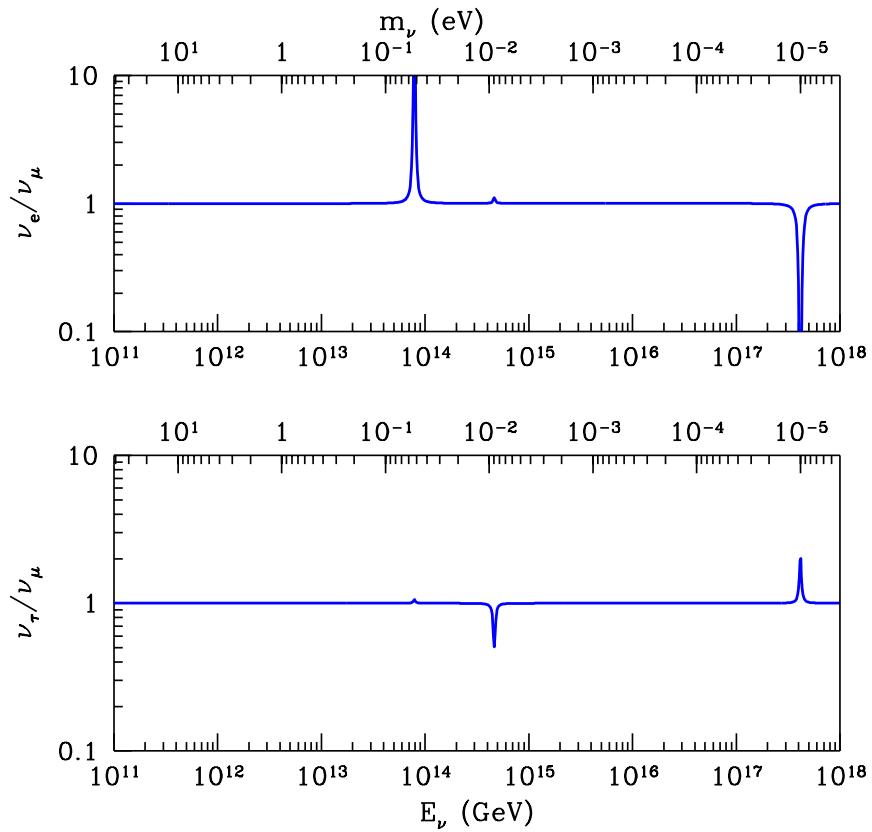


$$m_\ell = 10^{-5} \text{ eV}$$



$$m_\ell = 10^{-3} \text{ eV}$$

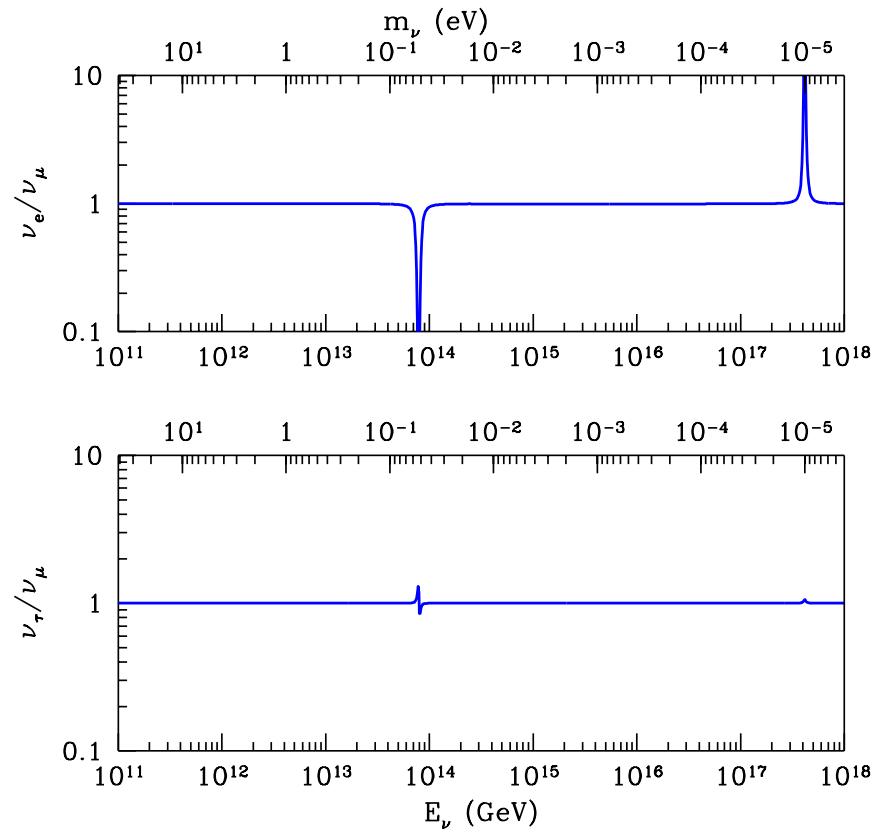
## Flavor ratios probe the mass hierarchy . . .



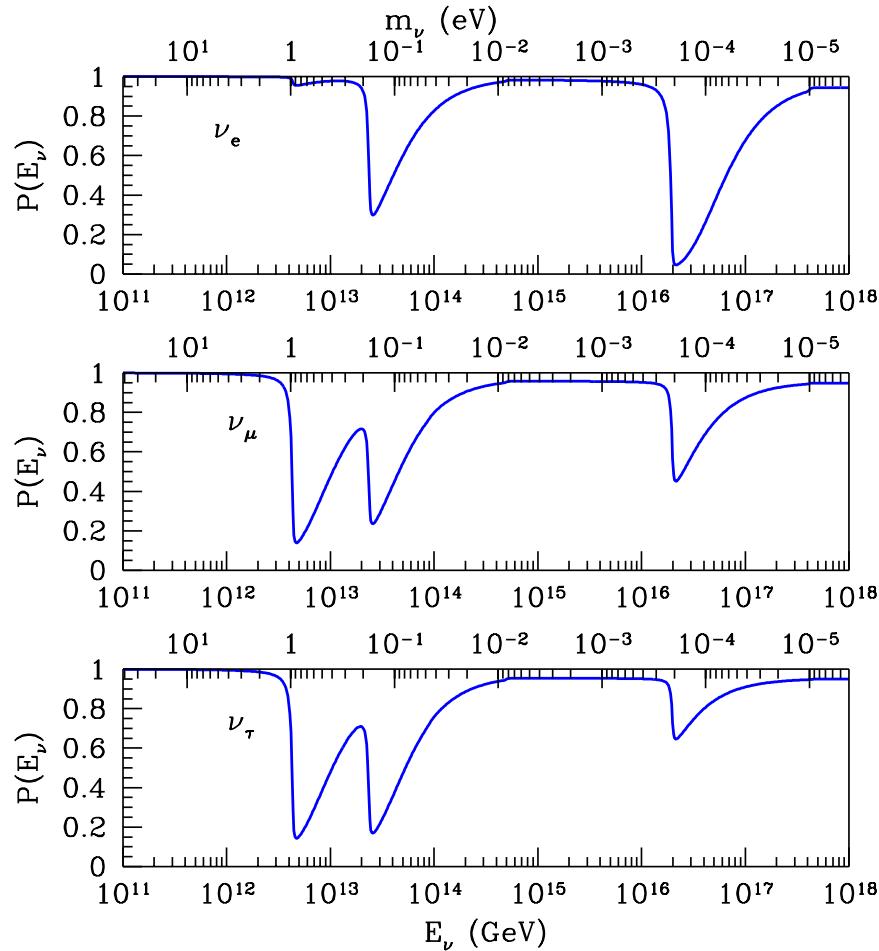
Normal

$$m_\ell = 10^{-5} \text{ eV}$$

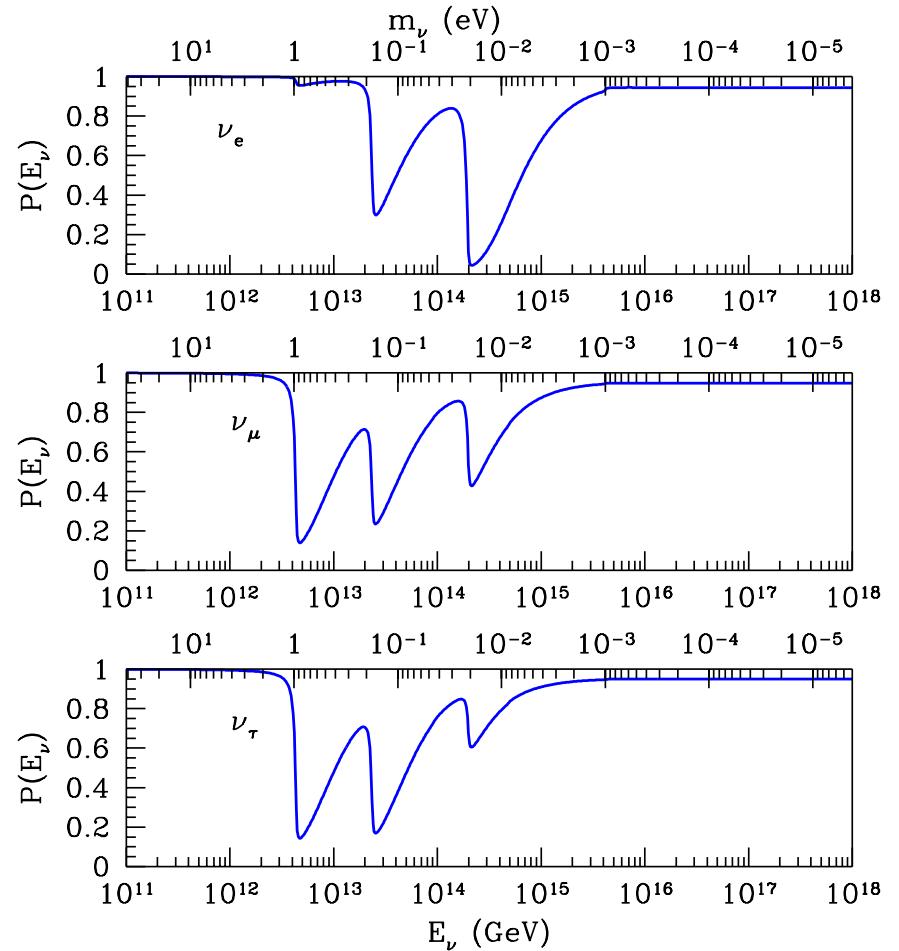
Inverted



## Incorporate evolution of Universe back to $z = 20$

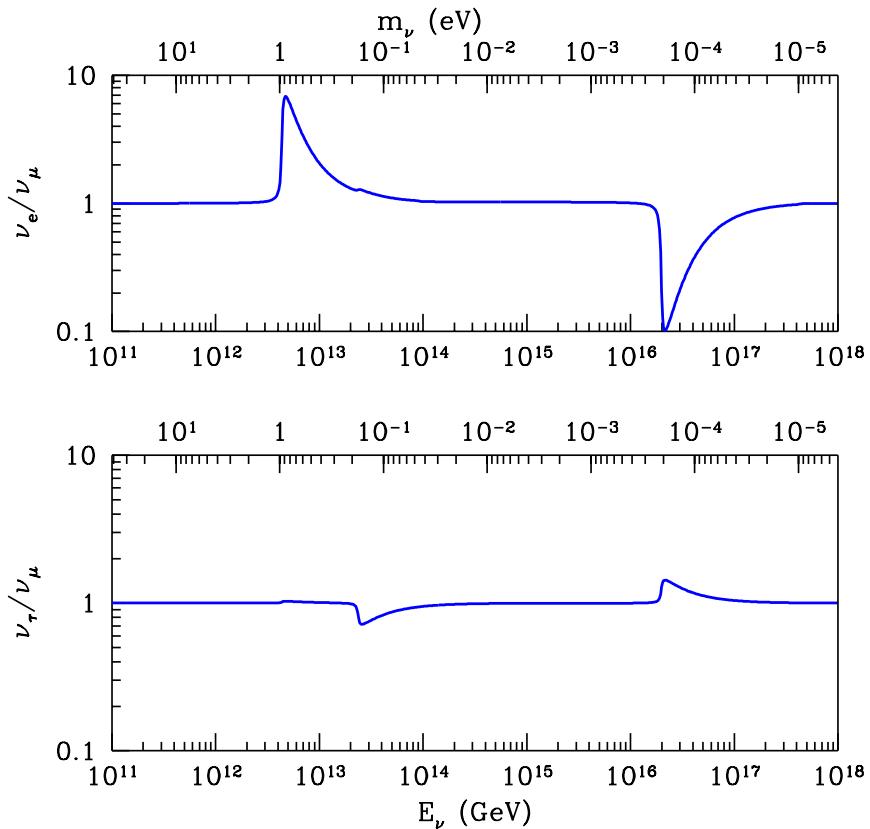


$$m_\ell = 10^{-5} \text{ eV}$$



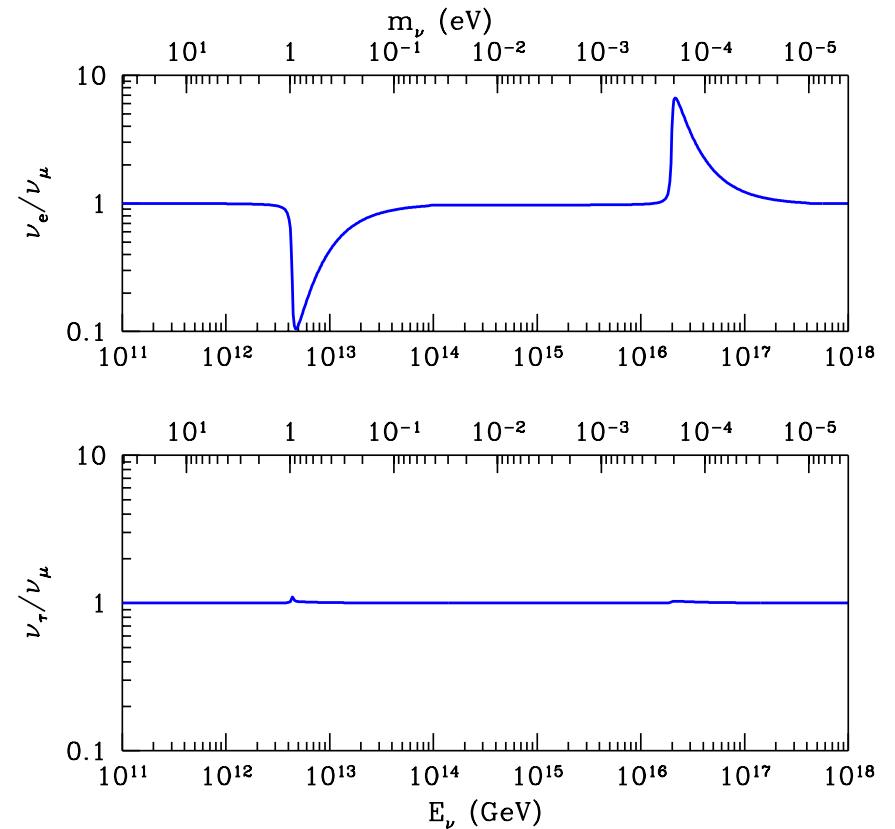
$$m_\ell = 10^{-3} \text{ eV}$$

## Flavor ratios probe the mass hierarchy ( $z \lesssim 20$ )



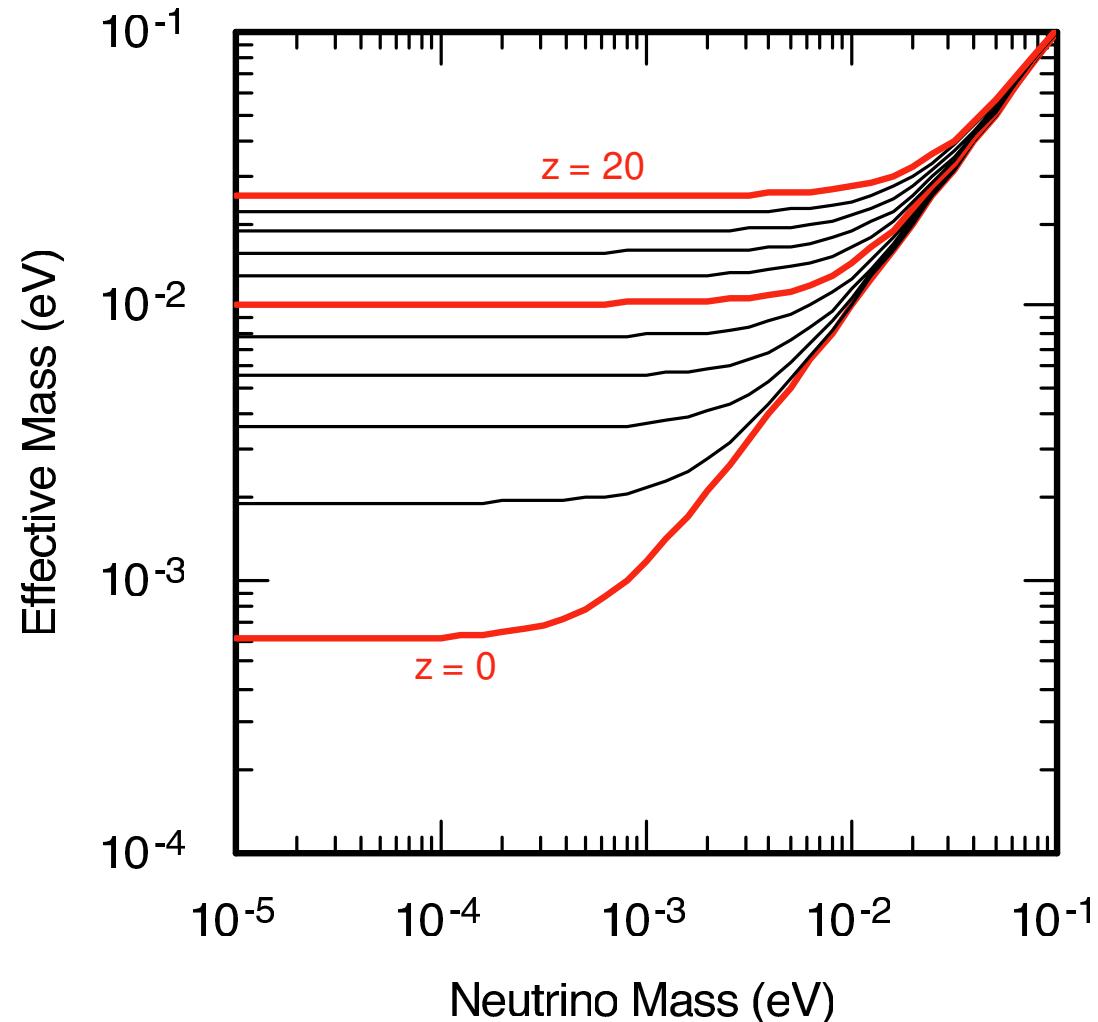
Normal

$$m_\ell = 10^{-5} \text{ eV}$$



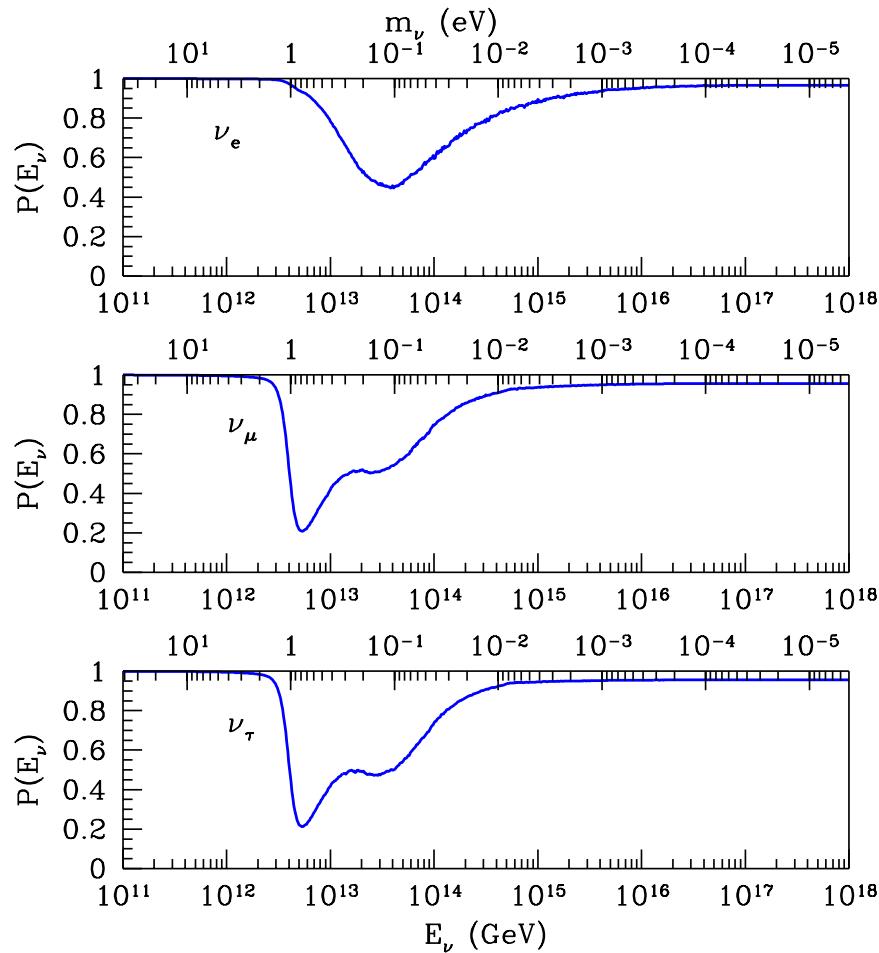
Inverted

## Neutrinos are moving targets . . .

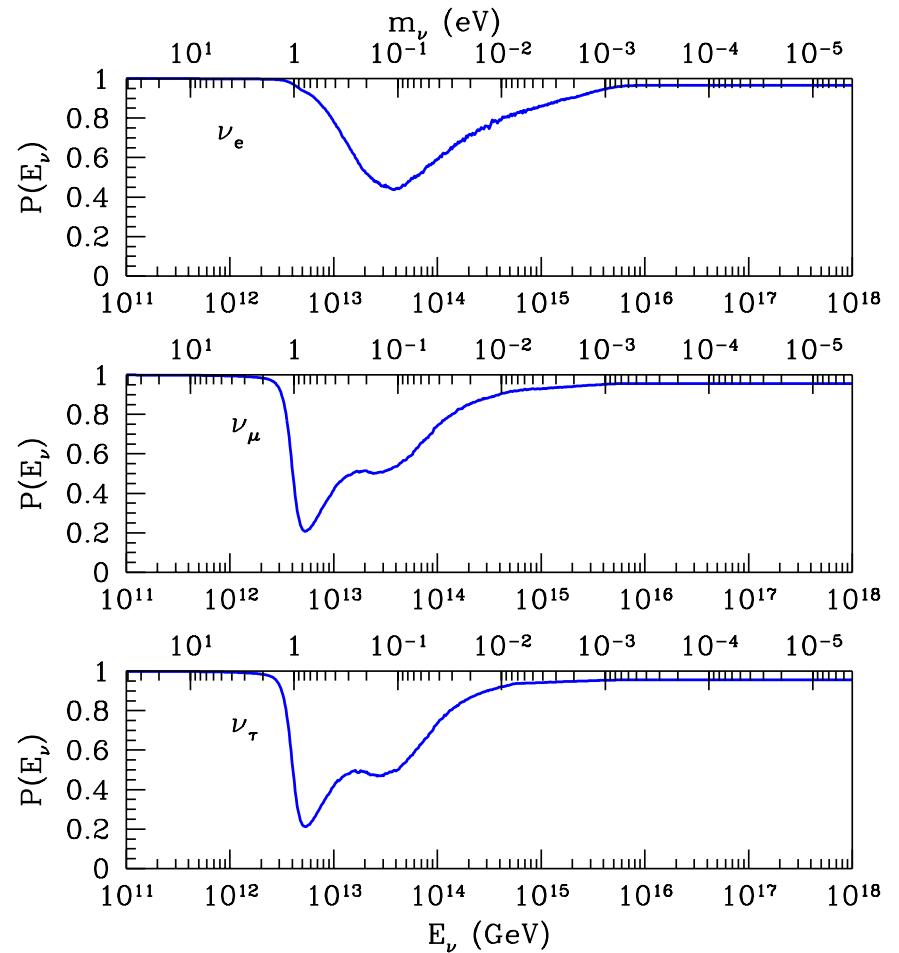


$$T_{\nu 0} = 1.945 \text{ K} = 1.697 \times 10^{-4} \text{ eV} \quad T_\nu \propto (1+z)$$

## Incorporate evolution of Universe back to $z = 20$ , Fermi motion

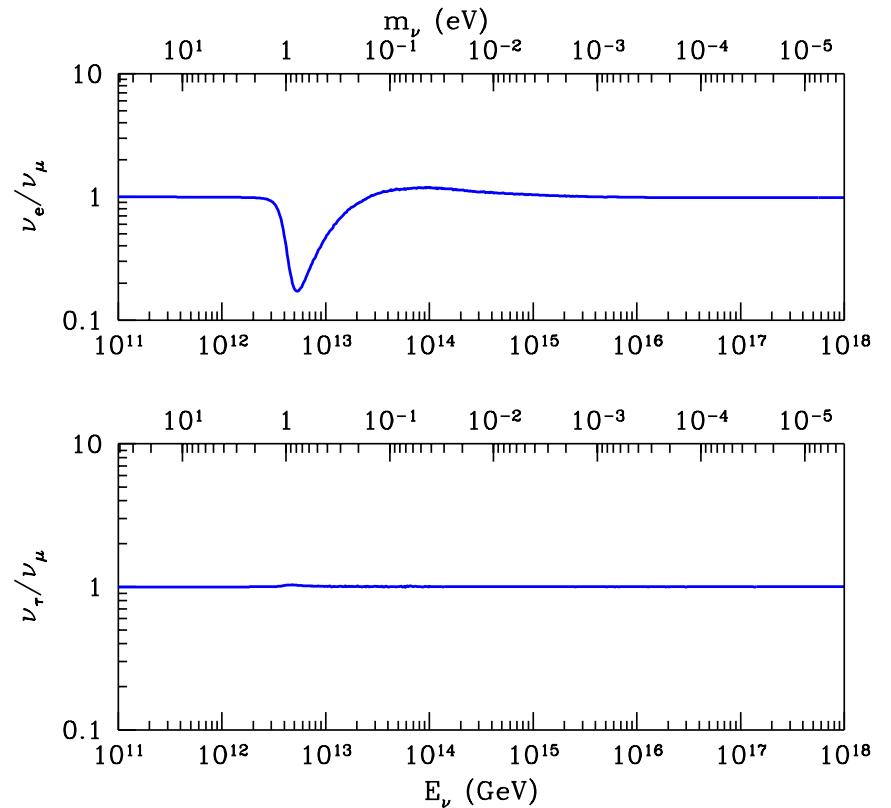
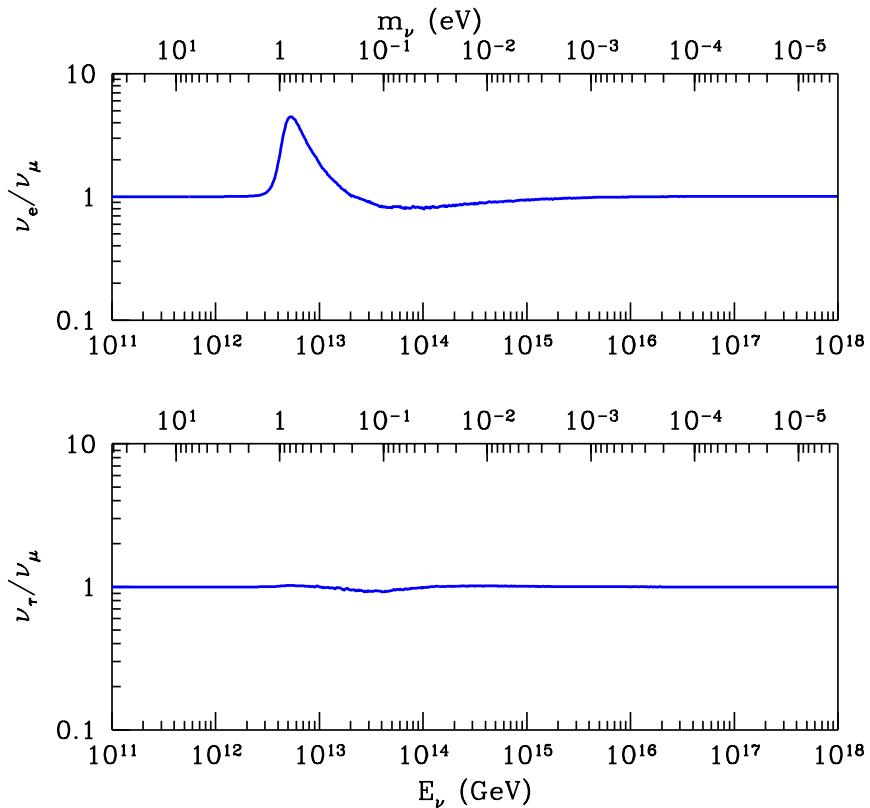


$$m_\ell = 10^{-5} \text{ eV}$$



$$m_\ell = 10^{-3} \text{ eV}$$

## Flavor ratios probe the mass hierarchy ( $z \lesssim 20$ ), Fermi motion



Normal

$$m_\ell = 10^{-5} \text{ eV}$$

Inverted

## *$z$ -dependence of column density imprinted on dips*

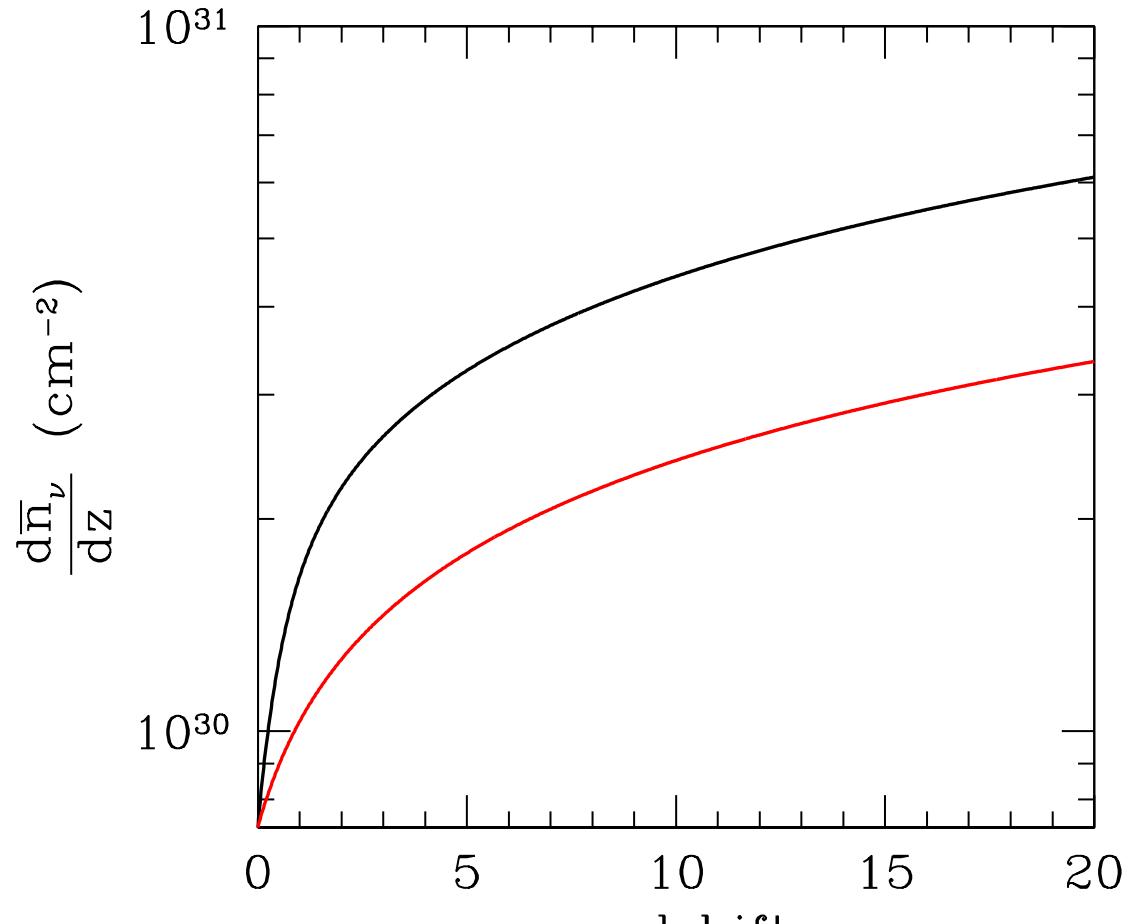
UHE  $\nu$  sources as standard candles?

Ability to discriminate grows with redshift

Early sources: differentiate quintessence models?

~ think about alternative thermal histories

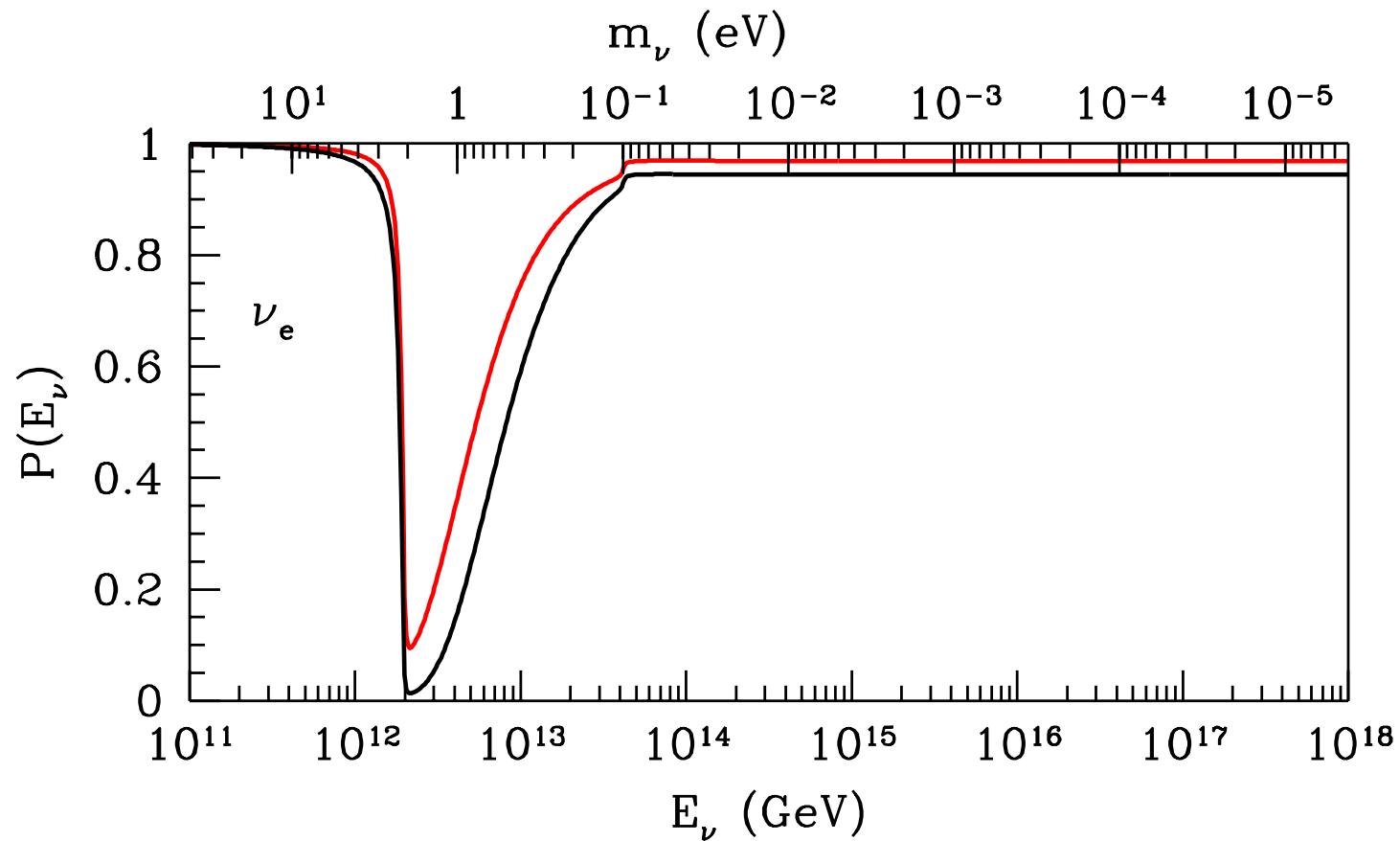
column density:  $d\bar{n}_\nu = n_{\nu 0}(1+z)^3 dr = \frac{n_{\nu 0}(1+z)^3 dz}{(1+z)H(z)}$



$\Lambda\text{CDM}$

$\text{SCDM}$  ( $\Omega_{\text{matter}} = 1$ )

$$m_\ell = 0.1 \text{ eV} \quad \int_0^{20} dz \cdots$$



$\Lambda$ CDM

SCDM ( $\Omega_{\text{matter}} = 1$ )

Exercise: look for a thermal history consistent with observations that makes an enormous effect on dips

- ☞ The fossil record is spotty:
  - BBN (few minutes)
  - decoupling era (379,000 y)
  - SN ( $z \approx 1$ )
  - Large-scale structure* (few % age now)
- ☞ Much room beyond  $\Lambda$ CDM (quintessence)
- ☞ Novel response to “why now” problem possible

## Evolving universe . . .

$$H^2 \equiv (\dot{R}/R)^2 = 8\pi G_N \rho / 3 - k/R^2 + \Lambda / 3$$

$$a \equiv R/R_0 \quad \rho_c = 3H^2/8\pi G_N \quad \Omega_{\text{tot}} = \rho/\rho_c$$

$$q \equiv -\frac{1}{H^2} \frac{\ddot{R}}{R} = \frac{\Lambda}{3H^2} - \frac{4\pi G_N}{3H^2} (\rho + 3p)$$

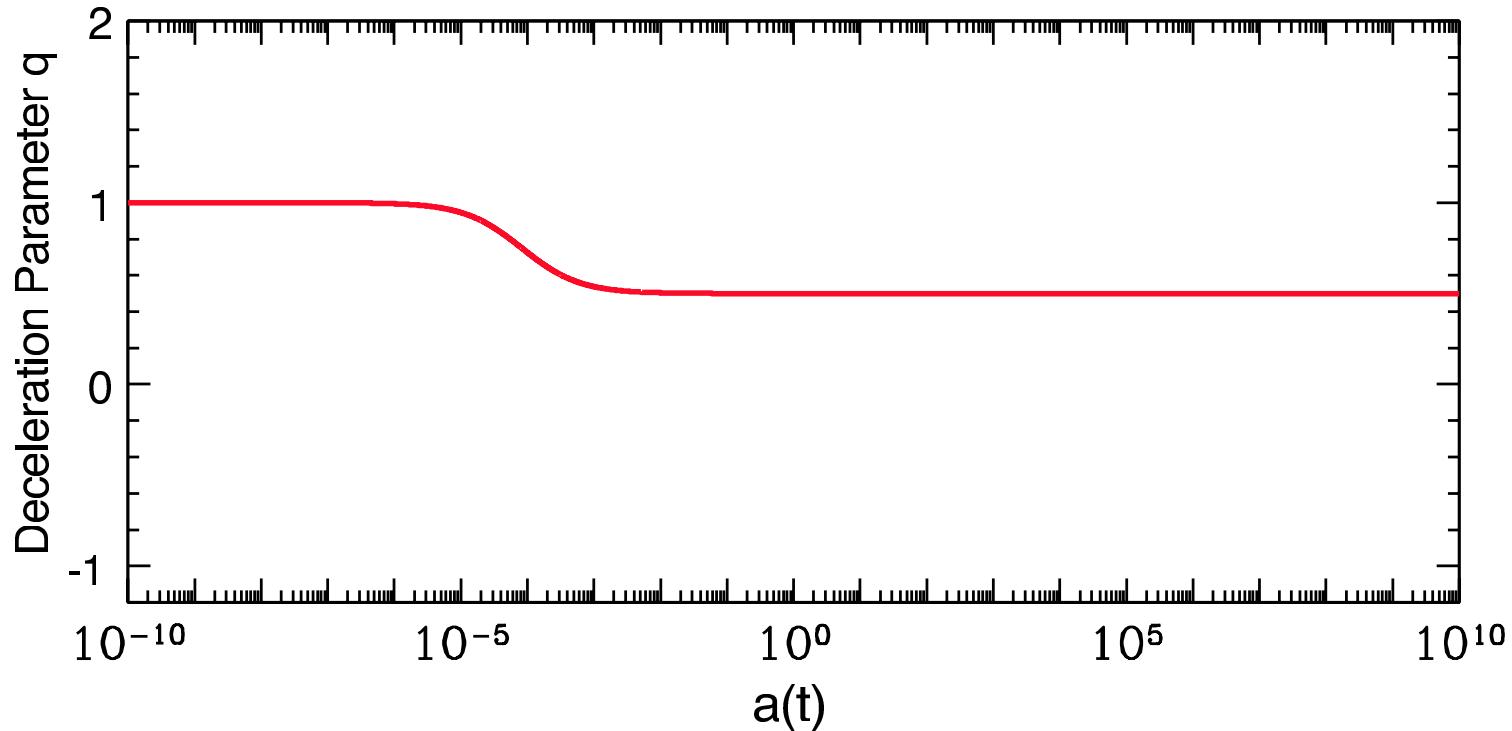
Define  $\Lambda = 4\pi G_N \rho_\Lambda$       Eqn of state:  $w_i = p_i/\rho_i$

$$q = \frac{1}{2} \sum_i \Omega_i (1 + 3w_i) = \frac{1}{2} (\Omega_{\text{tot}} + 3 \sum_i \Omega_i w_i)$$

$$w_m = 0 \quad w_r = \frac{1}{3} \quad w_\Lambda = -1$$

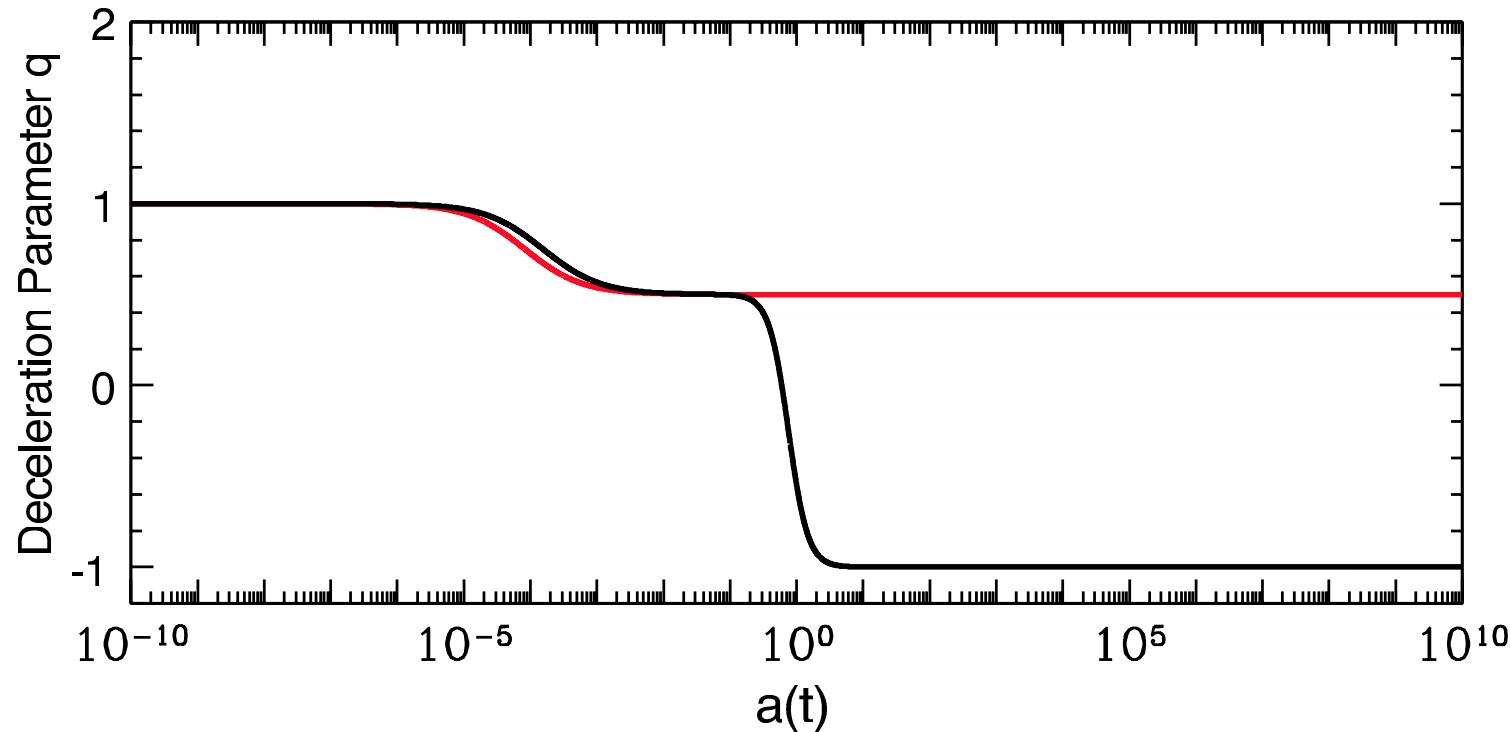
$$\text{SCDM: } \Omega_{\text{tot}} = \Omega_m = 1 \rightsquigarrow q_0 = \frac{1}{2}$$

# SCDM

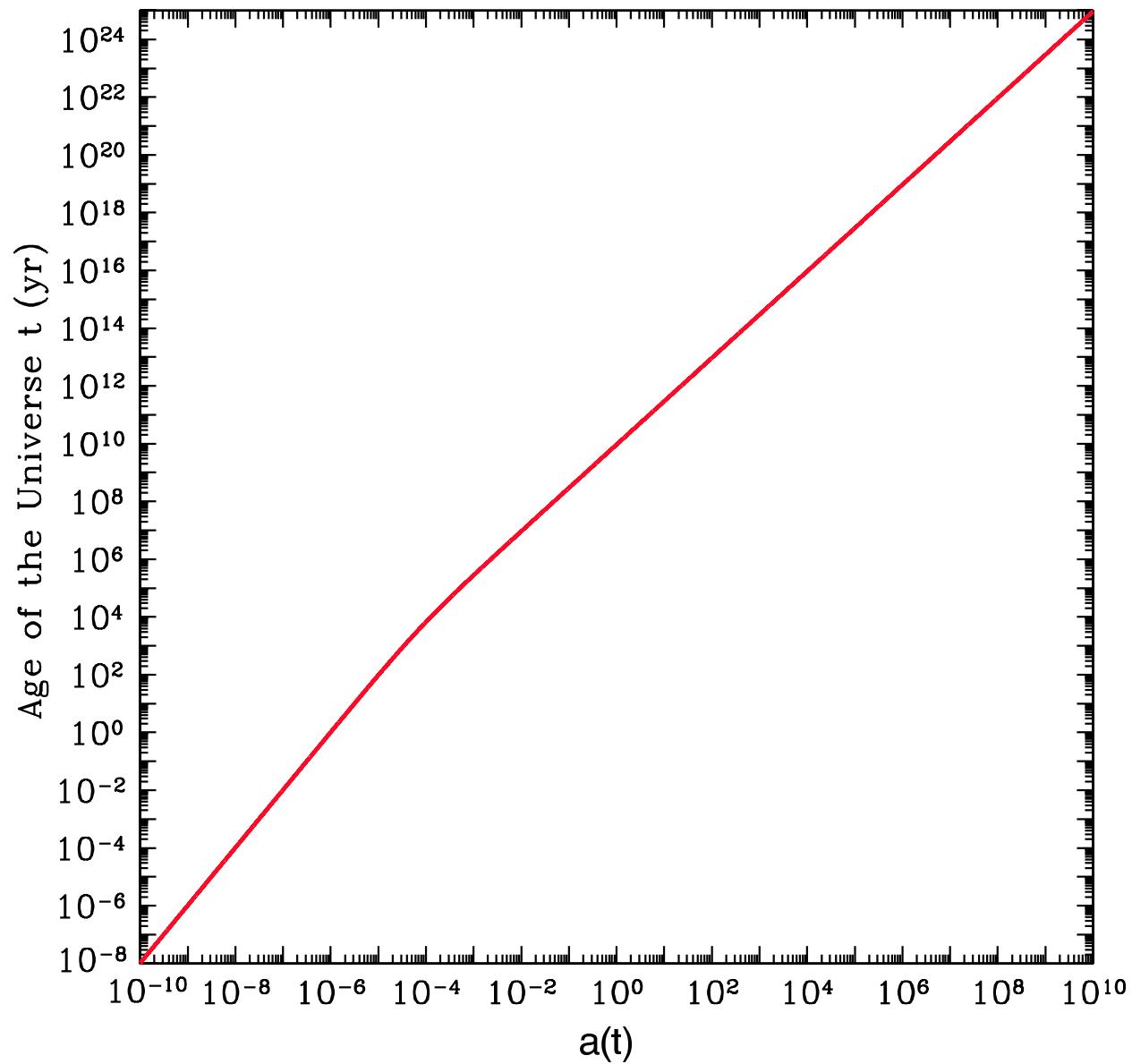


$SCDM$

$\Lambda CDM$

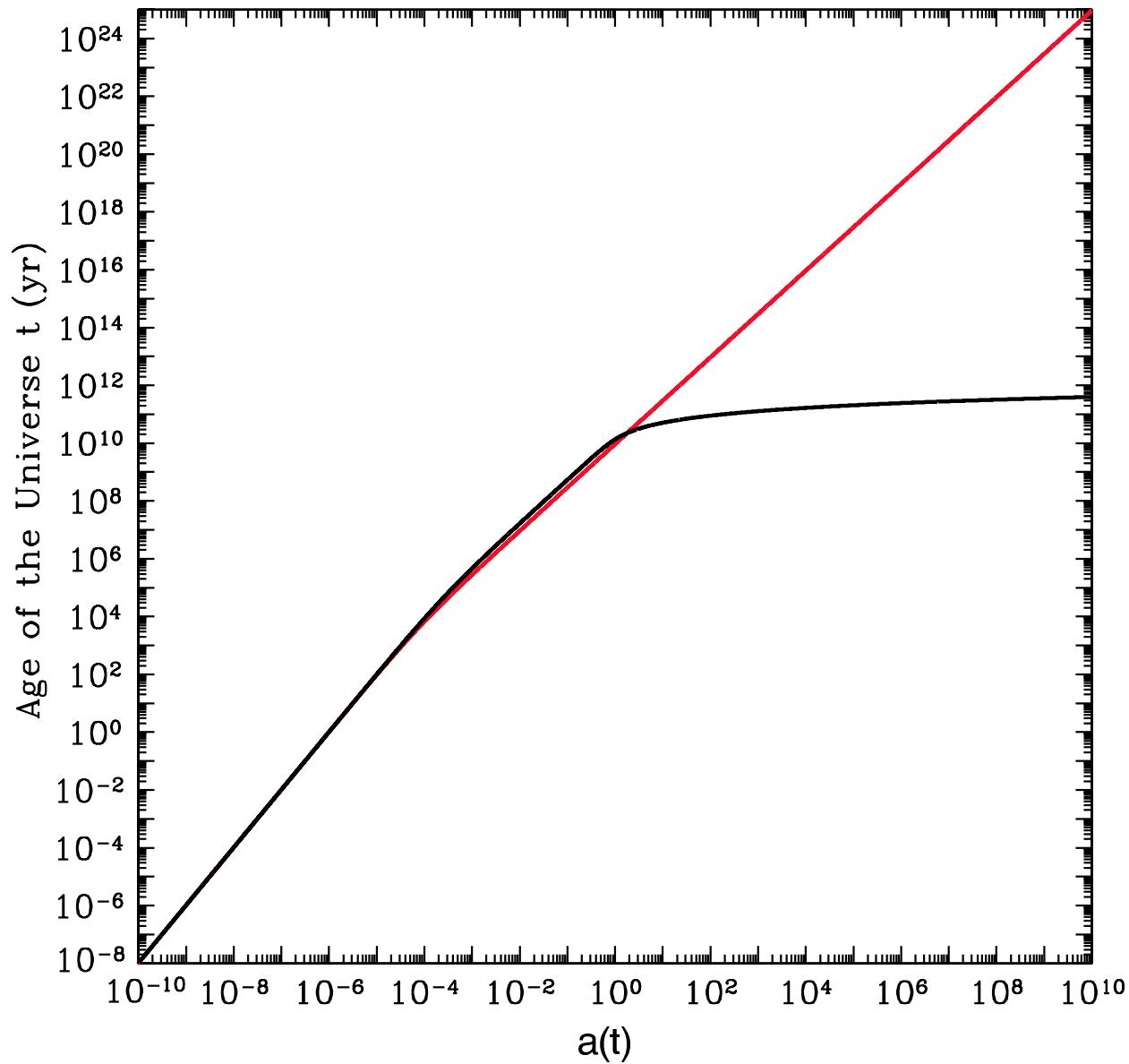


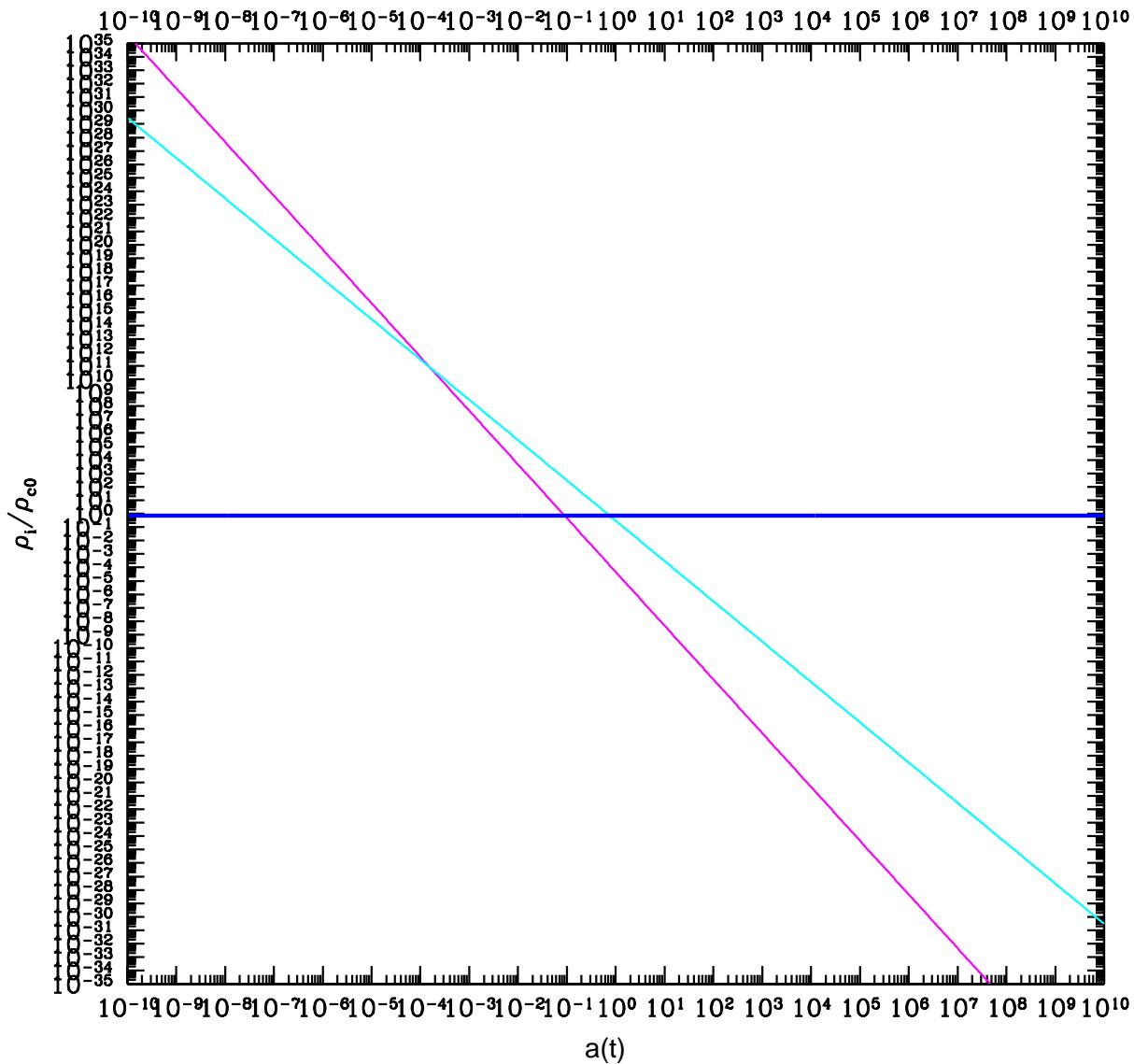
SCDM



$\text{SCDM}$

$\Lambda\text{CDM}$



$\Lambda$ CDM

Simple Ansatz:  $w_v(a) = -\cos(\textcolor{red}{b} \ln a)$

$$\Omega_{v0} = 0.7$$

$$\Omega_{m0} = 0.3$$

$$\Omega_{r0} = 4.63 \times 10^{-5}$$

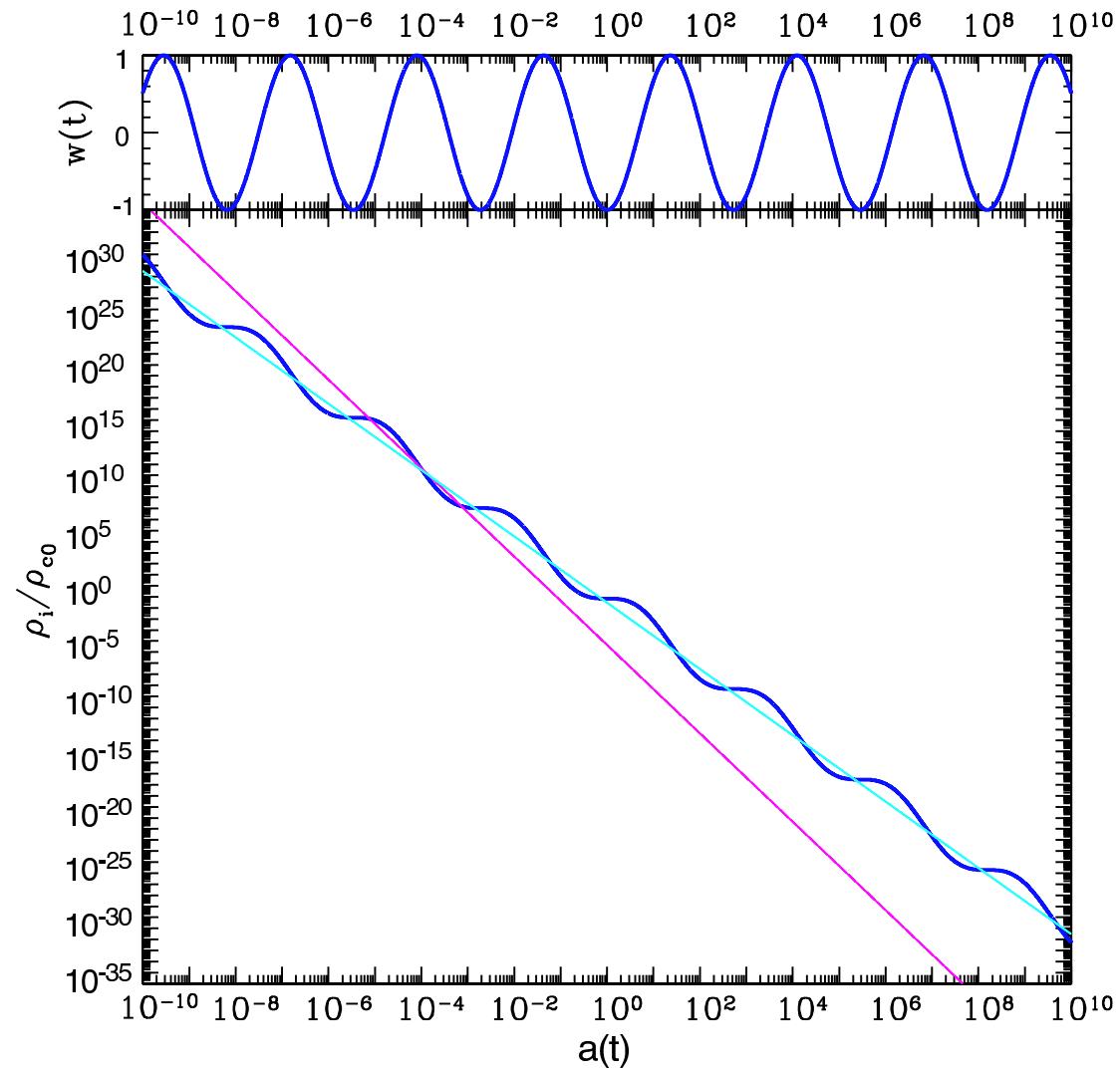
$$H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}, \text{ with } h = 0.71_{-0.03}^{+0.04}$$

$$\rho_v/\rho_{c0} = g(a)\Omega_{v0}/a^3, \text{ where}$$

$$g(a) = e^{3 \int_a^1 da' w(a')/a'} = \exp \left[ \frac{3}{b} \sin(b \ln a) \right].$$

*Gabriela Barenboim, Olga Mena, CQ*

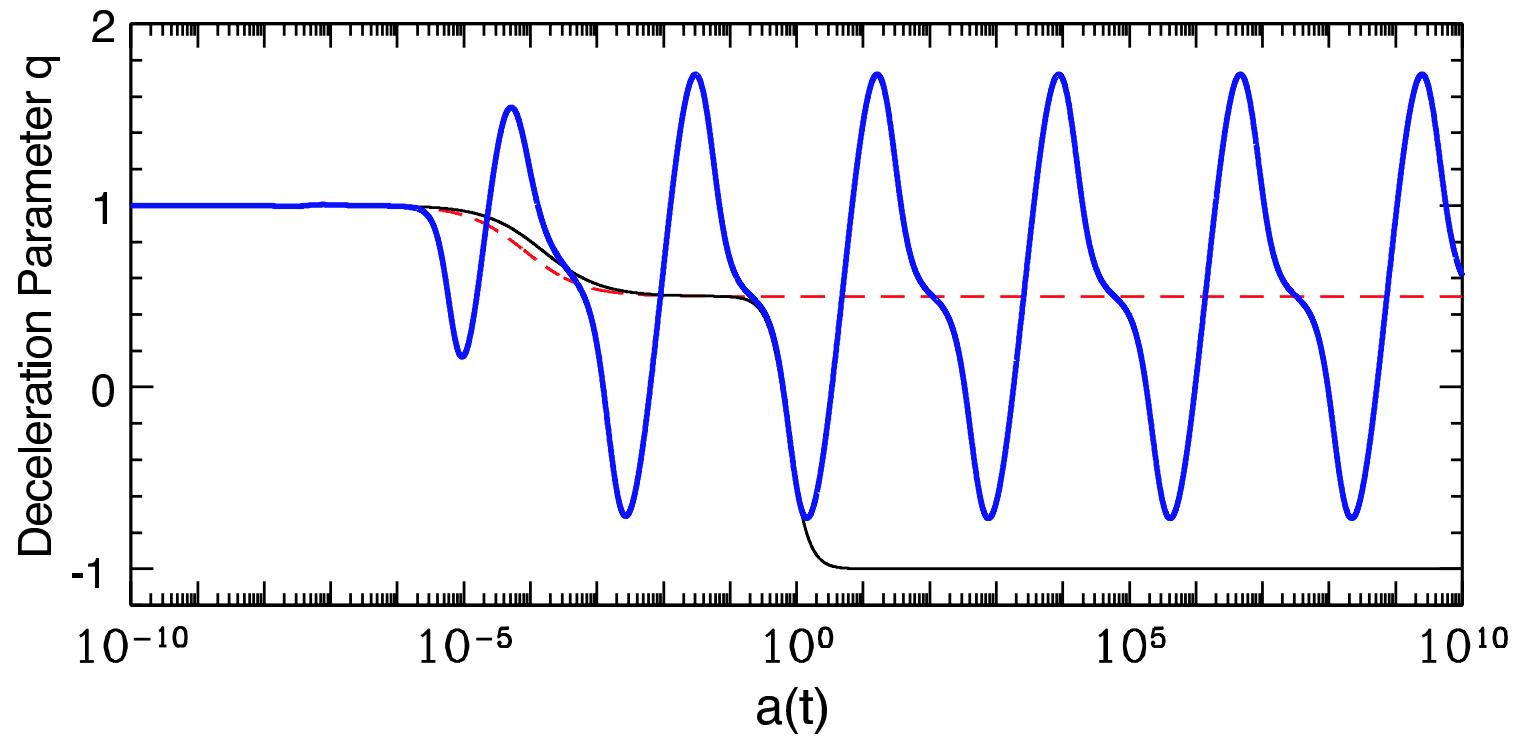
$$w_v(a) = -\cos \ln a$$



$\text{SCDM}$

$$w_v(a) = -\cos \ln a$$

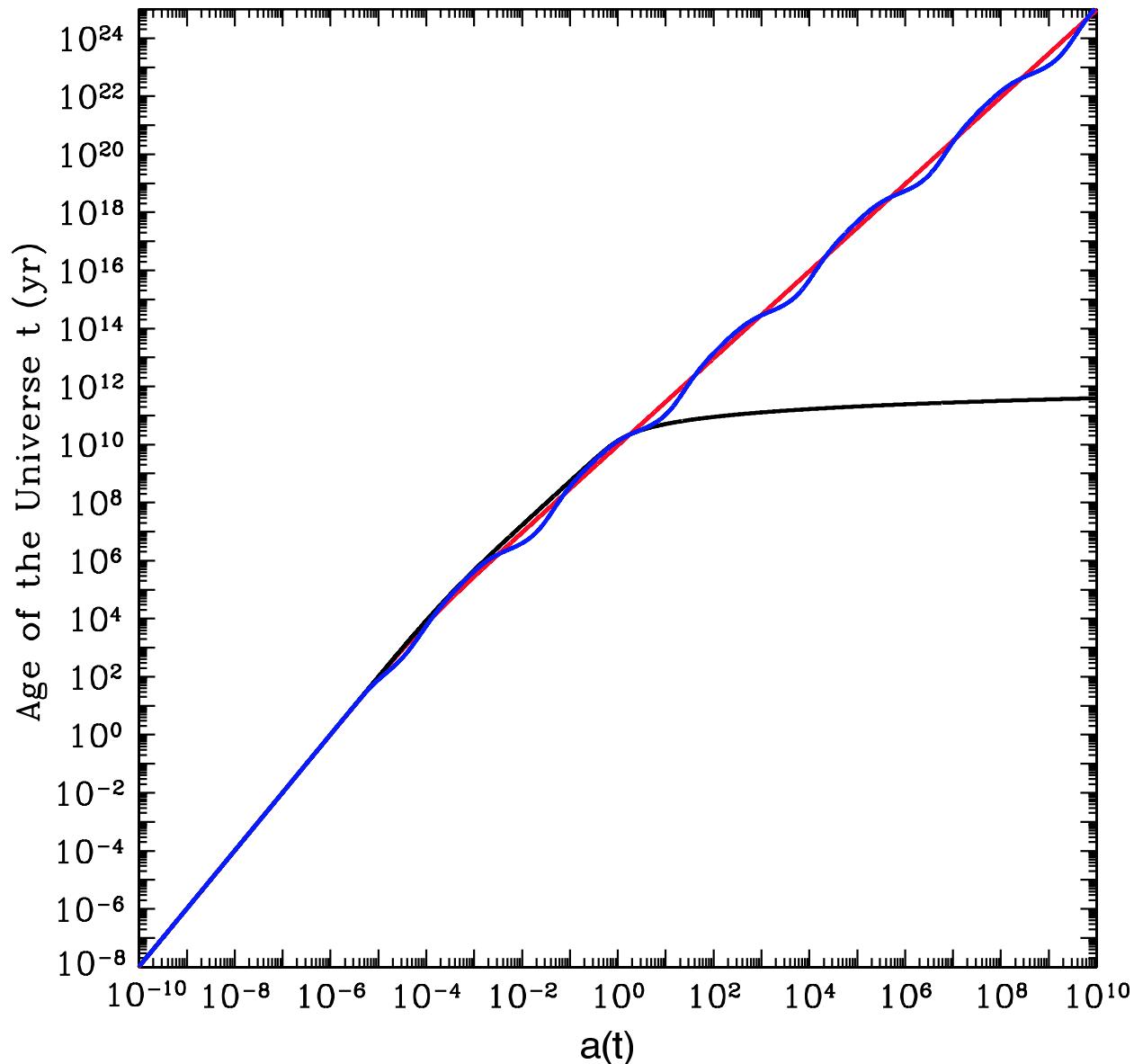
$\Lambda\text{CDM}$



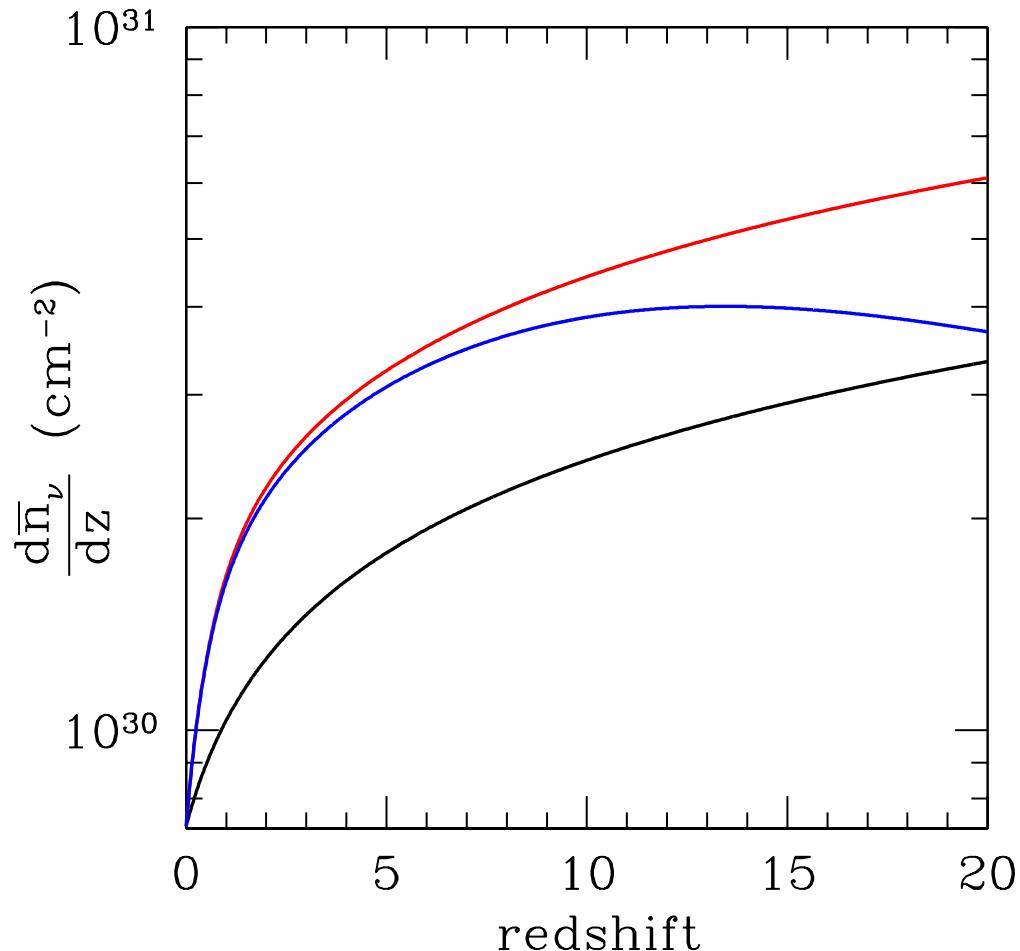
$\text{SCDM}$

$$w_v(a) = -\cos \ln a$$

$\Lambda\text{CDM}$



column density:  $d\bar{n}_\nu = n_{\nu 0}(1+z)^3 dr = \frac{n_{\nu 0}(1+z)^3 dz}{(1+z)H(z)}$



$\Lambda$ CDM

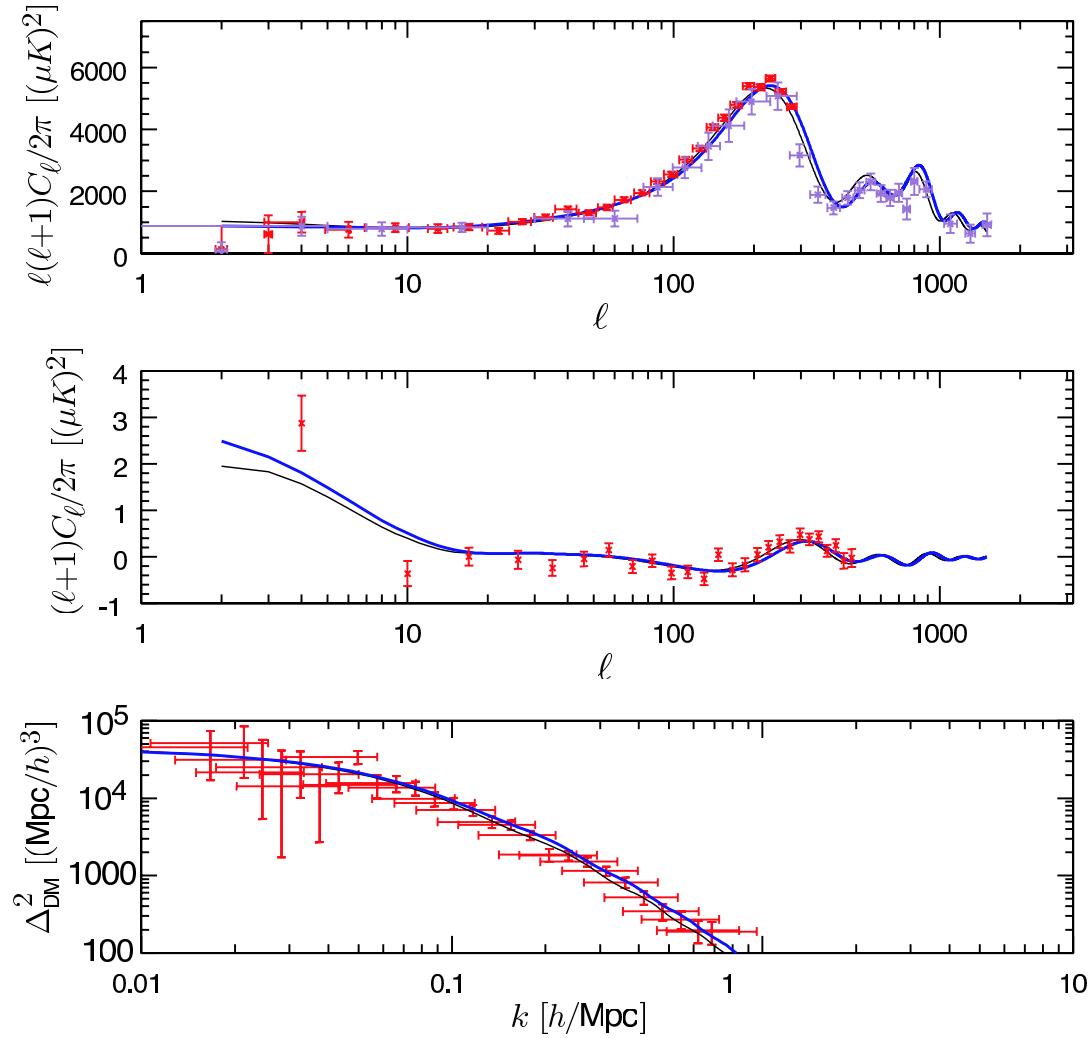
SCDM ( $\Omega_{\text{matter}} = 1$ )

$w_v(a) = -\cos \ln a$

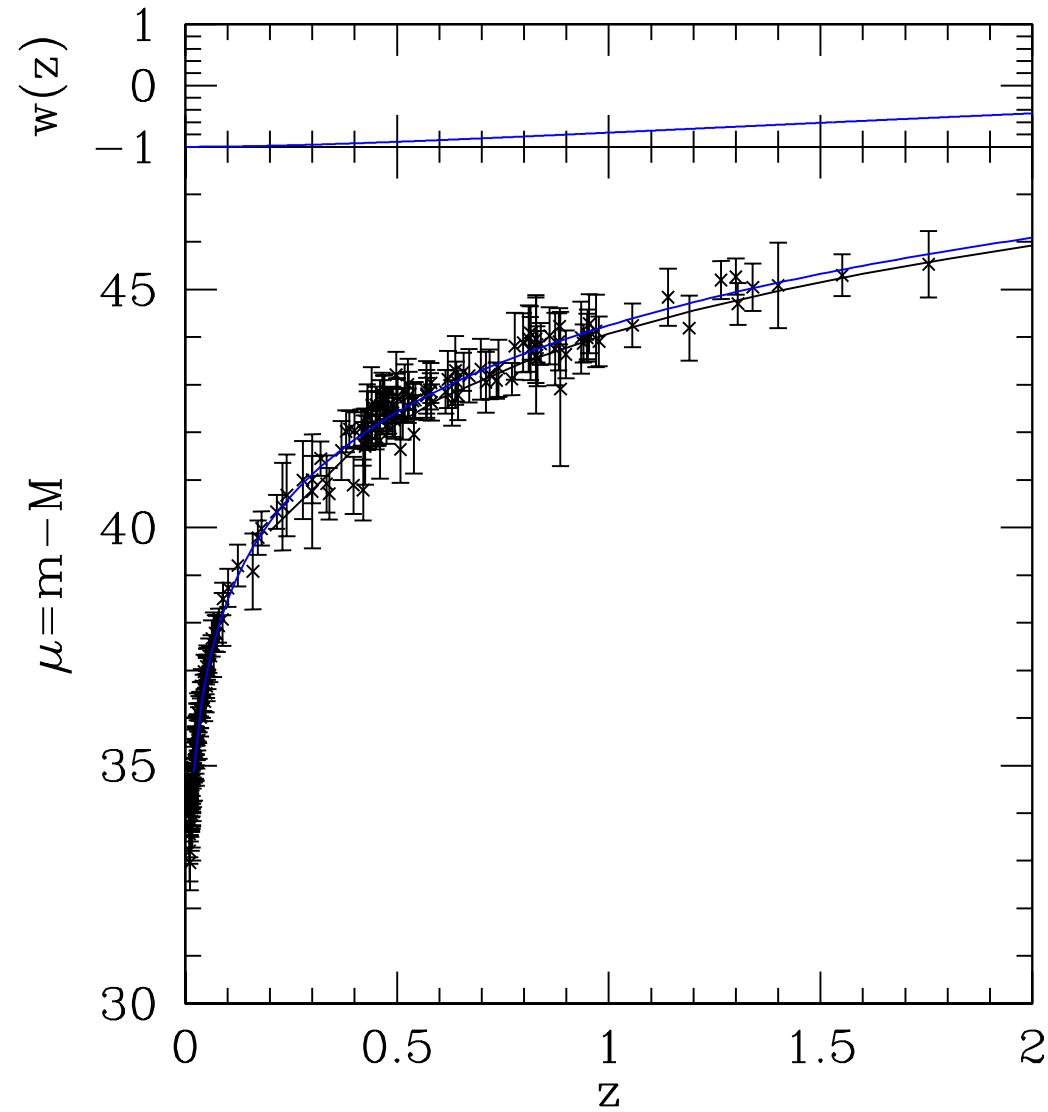
CMBFAST

$$w_v(a) = -\cos \ln a$$

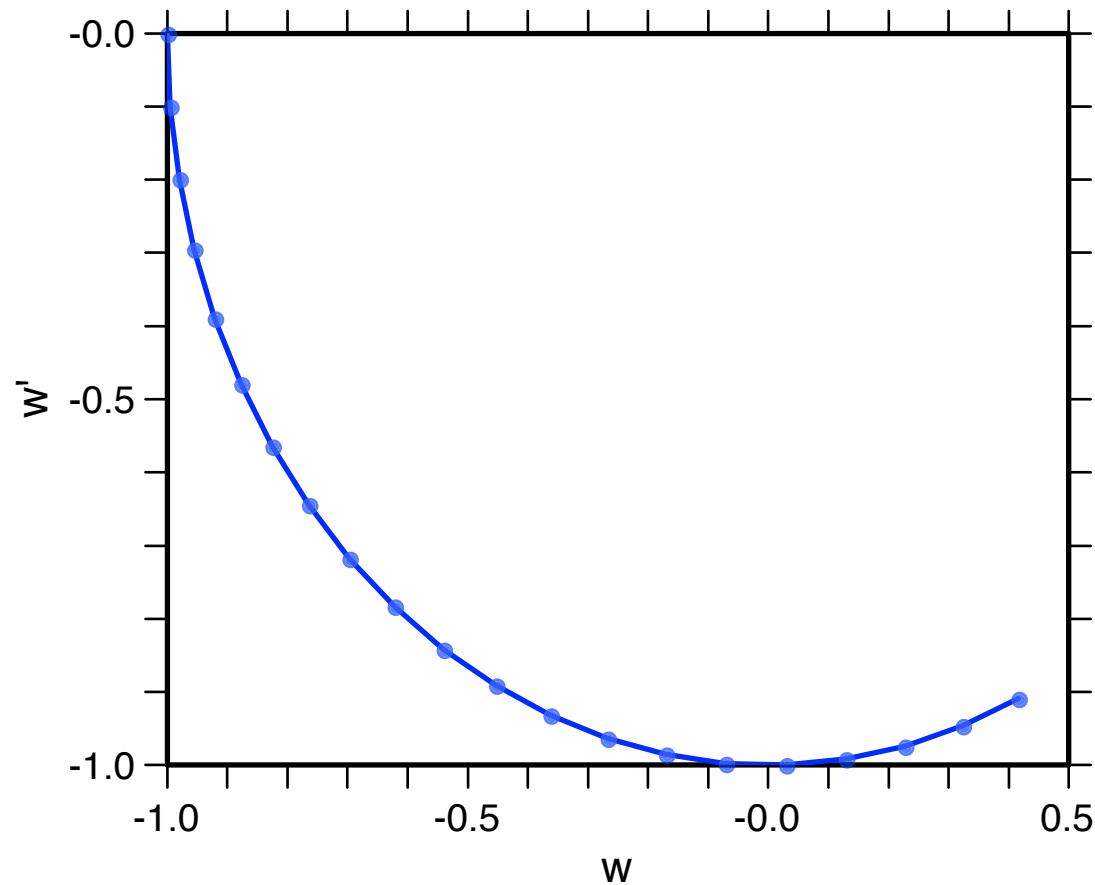
$\Lambda$ CDM



SN luminosity distance     $w_v(a) = -\cos \ln a$      $\Lambda$ CDM

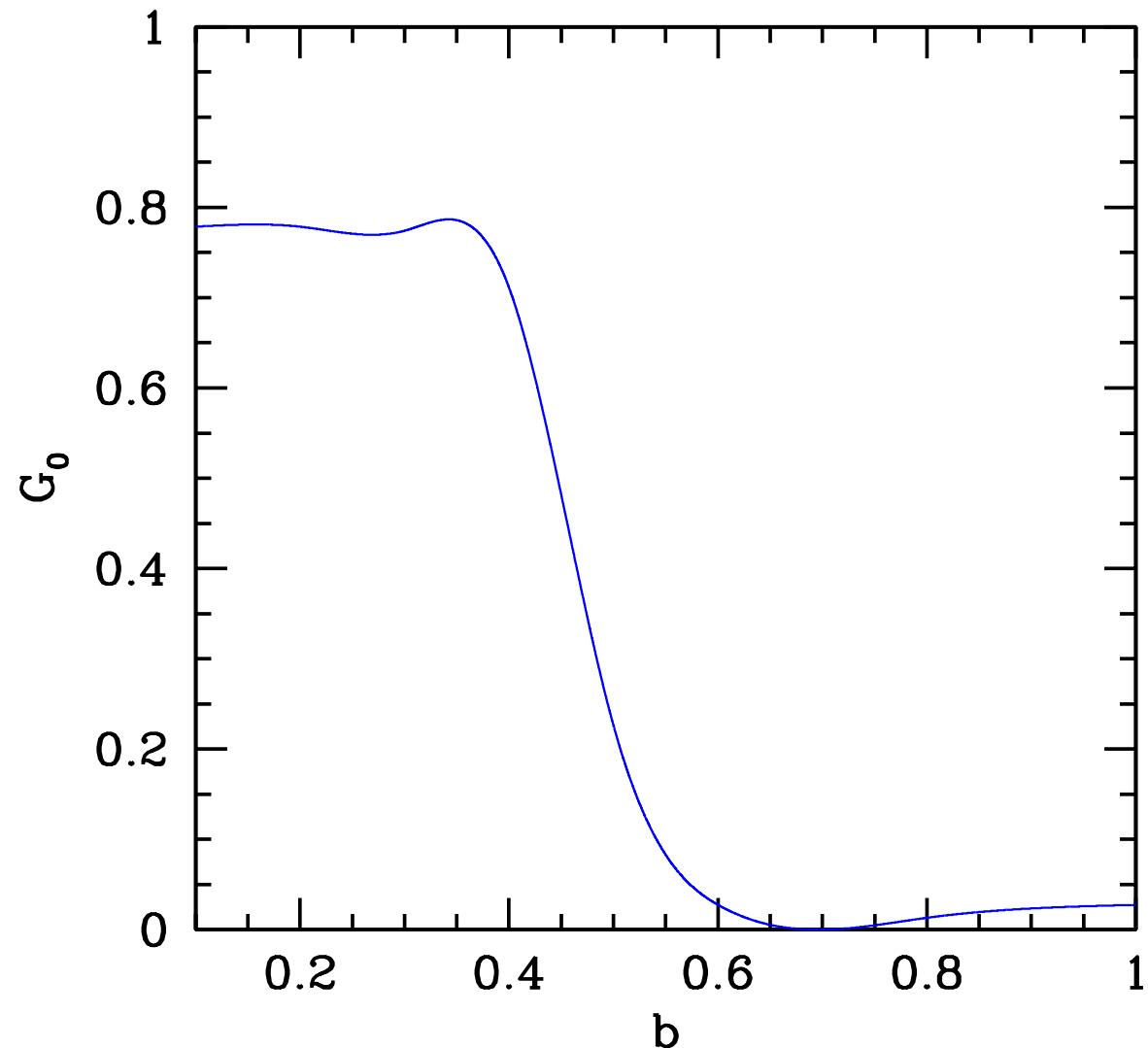


$$w_v(a) = -\cos b \ln a$$

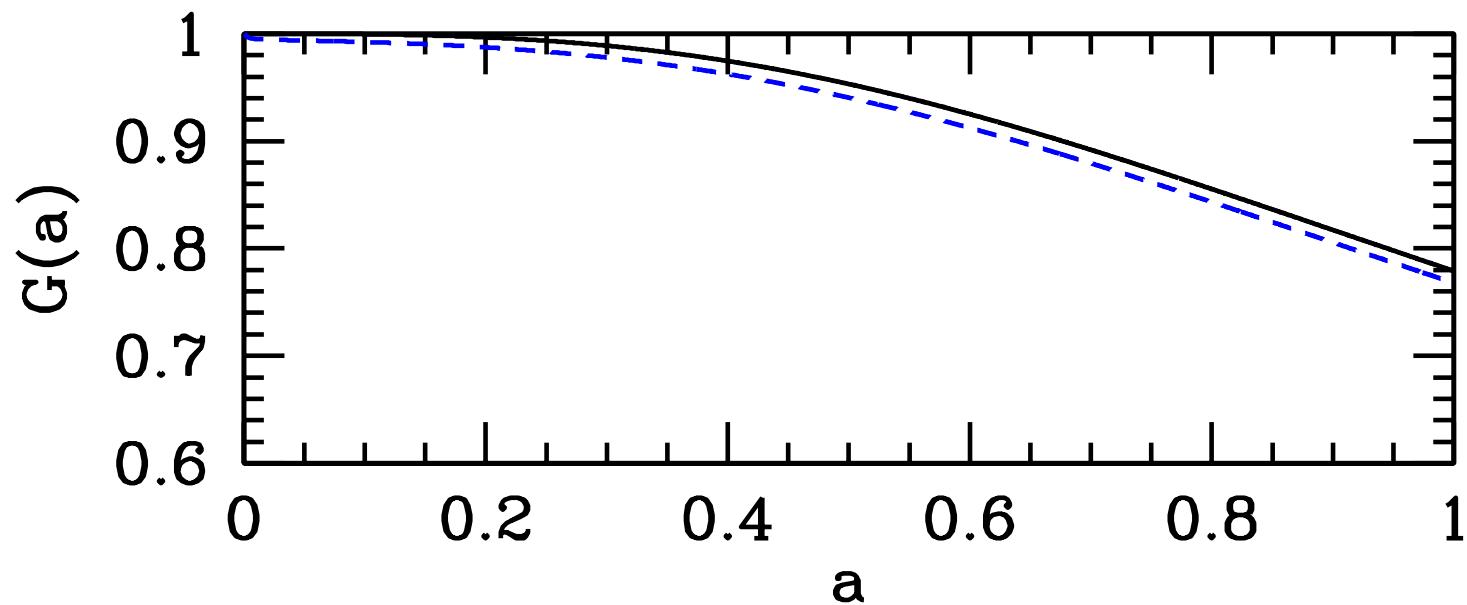


$$\text{step } \Delta \ln a = -0.1/b$$

*Linear Growth Factor*     $w_v(a) = -\cos b \ln a$



*Linear Growth Factor*  $w_v(a) = -\cos 0.4 \ln a$   $\Lambda$ CDM



## VII Neutrino Coannihilation on Dark-Matter Relics?

Consider neutralino dark matter,  $M_{\chi_1^0} \approx 150$  GeV

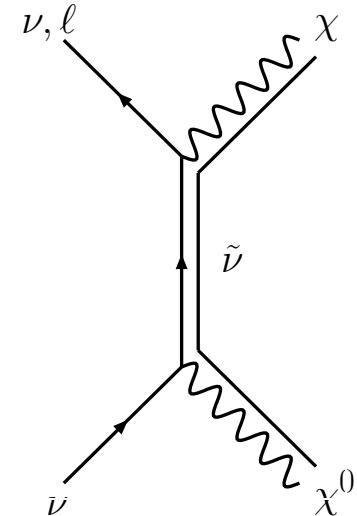
Good news:  $E_\nu^{\text{res}} \approx 400$  GeV ( $\tilde{\nu}$  formation);  
cross section 10% of  $\nu\bar{\nu} \rightarrow Z$

Bad news: relic  $\chi^0$  much rarer than relic  $\nu$

Universe at large:  $56 \nu \text{ cm}^{-3}$ ,  $\lesssim 10^{-8} \chi^0 \text{ cm}^{-3}$

Interaction length for  $\tilde{\nu}$  formation:  $10^{15}$  Mpc

Our location in galaxy [NFW]:  $\lesssim 10^{-3} \chi^0 \text{ cm}^{-3}$



Barenboim, Mena, CQ

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Good news:  $E_\nu^{\text{res}} \approx 400$  GeV ( $\tilde{\nu}$  formation);  
cross section 10% of  $\nu\bar{\nu} \rightarrow Z$

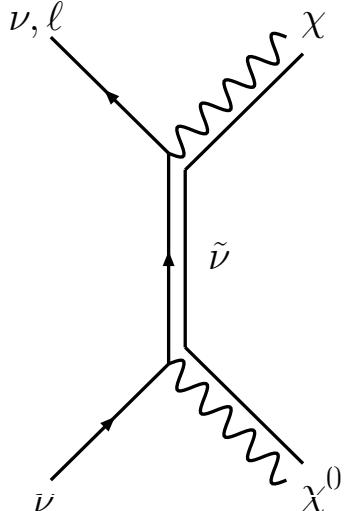
Bad news: relic  $\chi^0$  much rarer than relic  $\nu$

Universe at large:  $56 \nu \text{ cm}^{-3}$ ,  $\lesssim 10^{-8} \chi^0 \text{ cm}^{-3}$

Interaction length for  $\tilde{\nu}$  formation:  $10^{15}$  Mpc

Our location in galaxy [NFW]:  $\lesssim 10^{-3} \chi^0 \text{ cm}^{-3}$

Solar system, inside Earth orbit [Khriplovich & Pitjeva]:  $< 10^3 \chi^0 \text{ cm}^{-3}$



$$\sim < 10^{-6} \tilde{\nu} \text{ y}^{-1} \text{ in Earth's atmosphere (ATM } \nu)$$

... but up to  $O(600)$   $\tilde{\nu} \text{ y}^{-1}$  inside Earth's orbit (AGN  $\nu$ )

Barenboim, Mena, CQ

Datta, Fargion, Mele: UHE  $\chi^0$  on relic  $\nu$

$$\dots \nu \chi_1^0 \rightarrow \tilde{\nu}$$

Entire galaxy would contain  $\sim 10^{65}$  neutralinos (NFW profile)

With reasonable  $\nu$  flux,  $dN_\nu/dE_\nu \approx 5 \times 10^{-18} \text{ [GeV cm}^2 \text{ s sr}]^{-1}$ ,  
expect  $O(10^{24})$  coannihilations per year in the galaxy

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Few-GeV  $\gamma$  signals from inelastic decay channels, *most prominent for  $\nu_\tau$*   
... for the right kind of neutralino dark matter (GLAST regime)

... but we would detect only  $O(10^{-21}) \text{ cm}^{-2} \text{ y}^{-1} \sim$  hopeless!

## VIII Gravitational Lensing of Neutrinos?

*How demonstrate that neutrinos have normal gravitational interactions?*

Pound–Rebka experiment exploiting Mössbauer effect? Raghavan

Arrival time of SN1987A neutrinos, photons Longo, Krauss & Tremaine

Lack steady sources, angular resolution to see deflection by the Sun

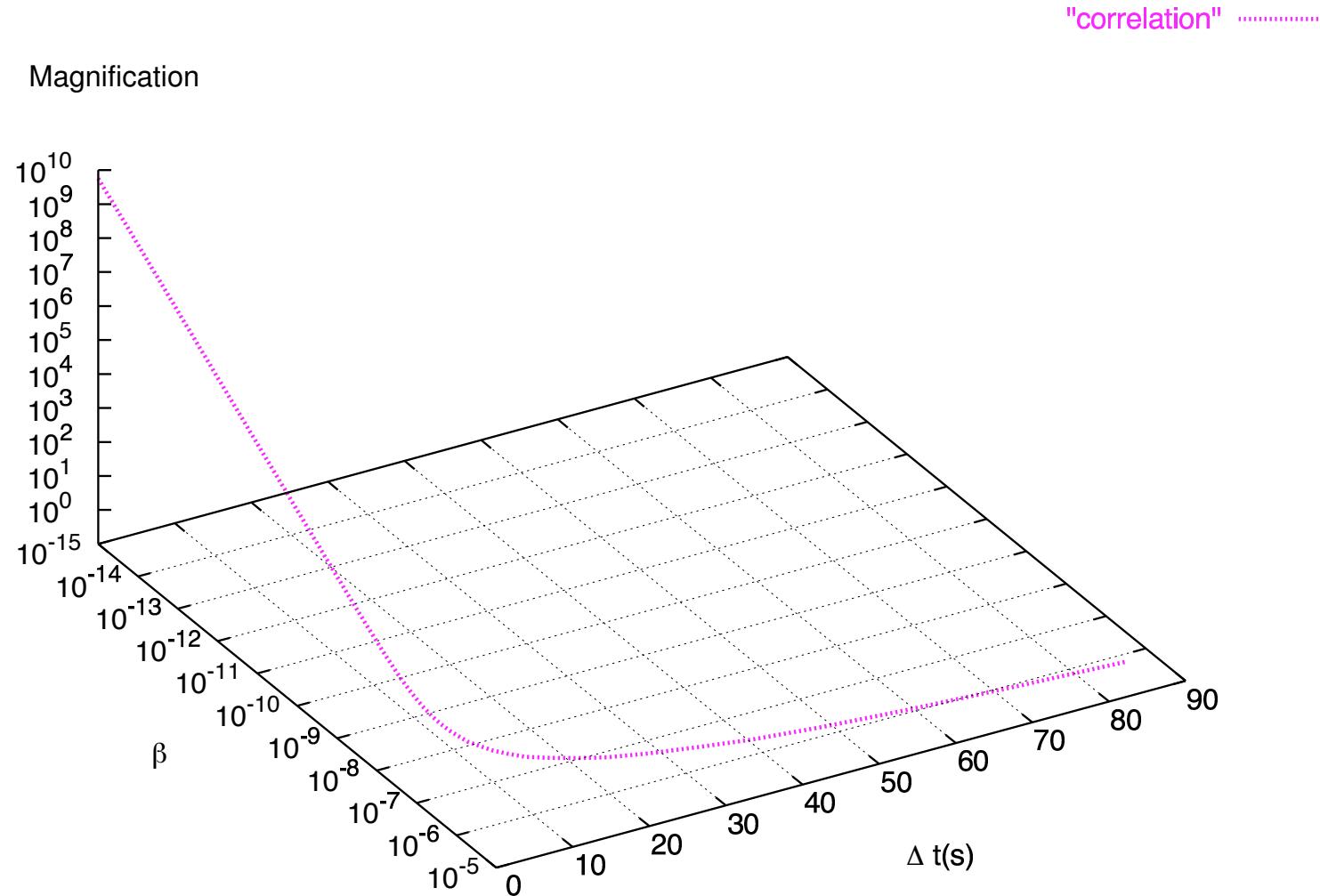
Lensing Supernova neutrinos by black hole at galactic center:  
significant amplification, time dispersion

For symmetric case,  $\beta \equiv$  misalignment angle,  $\theta_E^2 = 2\mathcal{R}/D_{OS}$ :

Magnification:  $\mu \approx \theta_E/\beta$  Time dispersion:  $\Delta t \approx 53 \text{ s} \cdot (\beta/\theta_E)$

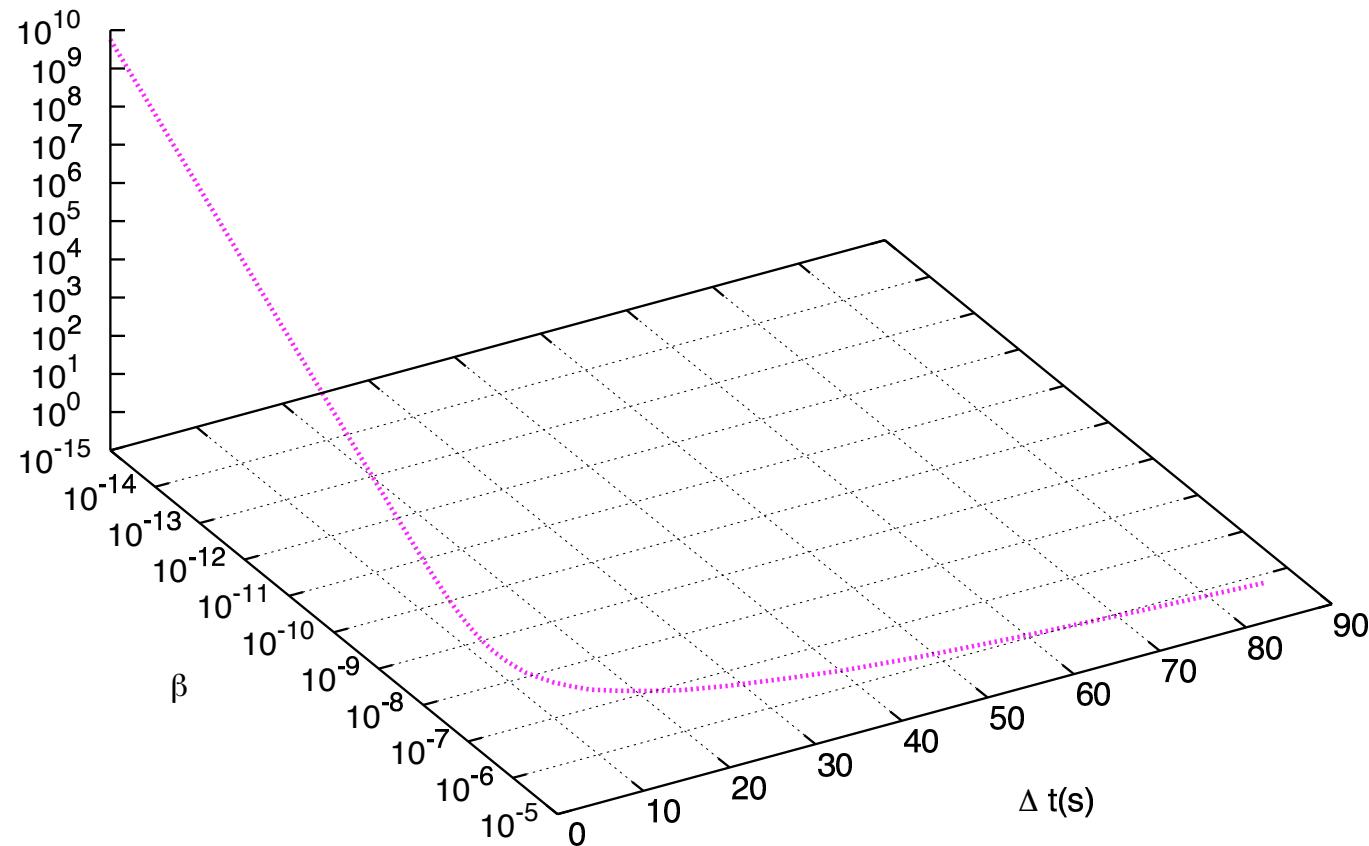
Mena, Mocioiu, CQ

Magnification



Magnification

"correlation" .....



"It is a part of probability that many improbable things will happen."

George Eliot (after Aristotle), *Daniel Deronda*

## From Neutrino Astronomy to Particle Physics

Prospects for probing particle physics in neutrino telescopes will be greatly enhanced by

- recording, characterizing energy of NC events
- neutrino flavor tagging, with energy measurement
- attention to surprises (e.g., misplaced absorption lines)
- sensitivity to TeV- $\gamma$  signals from  $\nu$  coannihilation ( $\gamma$ -ray telescopes)
- SN neutrino bursts from other side of our galaxy